NASA Contractor Report 198532

Technology Directions for the 21st Century

Volume III

Giles F. Crimi, Robert Botta, Thomas Ditanna, Henry Verheggen,
Michael Stancati, Harvey Feingold, and Mark Jacobs
Science Applications International Corporation
McLean, Virginia

September 1996

Prepared for
Lewis Research Center
Under Contract NAS3–26565

National Aeronautics and
Space Administration

PREFACE

In this rapidly changing world, effective governmental organizations must constantly anticipate and regularly plan for the future. For NASA, the process of doing this has become particularly challenging. Global economic strategies have greatly increased the need for cooperative partnerships to provide adequate resources for space science and exploration programs. Nationally, both fiscal considerations and an underlying Administration mandate to reinvent government have caused reorganization and privatization within NASA of an unparalleled magnitude. NASA's focus is to emphasize completing missions faster, cheaper and better, without compromise to safety or scientific value.

Clearly, our technology strategies must correspondingly change with this revised set of paradigms. Today's technological advances provide ample opportunities to improve the ways in which NASA carries out its responsibilities and serves its customers. NASA's future technology emphasis must focus on dual-use activities; that is, technology must be transferred or leveraged with other government agencies, industrial partners, international counterparts, and academia to share costs, exchange technical knowledge, support a growing economy, and provide technological leadership for our nation. NASA now has the opportunity, as never before, to shop the marketplace for technologically sophisticated data and information communications systems and services. The competitiveness of commercial ventures, such as those ignited by the deregulation of the telephone industry, has shifted the burden of continuously developing cutting-edge technology from government to the commercial sector.

The rapidly evolving worlds of terrestrial and satellite systems communication technologies described in this report provide many potential opportunities for shopping the market place. For terrestrial networks, new technologies continue to support the ever increasing demand for bandwidth. In addition, a shift from private to public networks is underway as public networks achieve higher levels of availability and reliability, and offer a flexible menu of services. As for satellite communications, this report discusses over $18B in investments for low Earth orbiting data and voice communications systems. In general, the distinctions among long- and short-haul carriers, telephone and cable operators, wireless and wired networks, data and video are becoming increasingly blurred. Private investments in communications infrastructure now significantly exceed the budget for communications investments in agencies the size of NASA.

This is the third volume of a series of technology applications reports. These reports focus on the continuing effort to predict and understand technology trends to better plan development strategies. The objectives of this series of documents are to: (1) validate, revise or expand relevant technology forecasts; (2) develop applications strategies to incorporate new technologies into our programs; and, (3) accomplish Agency goals while stimulating and encouraging development of commercial technology sources. Volumes I, II and III, together with a future Volume IV, summarize several studies relevant to communication and data processing technologies selected for their appropriateness to meet our challenges.

Comments from interested parties would be especially appreciated, and may be directed to NASA Headquarters, Dr. Albert R. Miller, at (202) 358-4804, or to NASA Lewis Research Center, Ms. Denise S. Ponchak, at (216) 433-3465.

Dr. Albert R. Miller

Dr. Albert R. Miller
Assistant Associate Administrator (Plans)
Office of Space Communications
NASA Headquarters

ACKNOWLEDGMENT

This work was performed by Science Applications International Corporation (SAIC), Software and Systems Integration Group, in McLean, Virginia for the National Aeronautics and Space Administration (NASA). This report summarizes a series of investigations of various technologies which are important to long range planning for the operational systems and capabilities for which NASA's Office of Space Communications is responsible.

NASA is pleased to acknowledge the following SAIC personnel who contributed to this effort: Dr. Giles Crimi (Program Manager); for Chapter 1, Dr. Robert Botta (Principal Investigator), Mr. Thomas Ditanna (Contributing Investigator); and for Chapter 2, Messrs. Henry Verheggen and Michael Stancati (Principal Investigators), and Dr. Harvey Feingold and Mr. Mark Jacobs (Contributing Investigators).

The technical direction for this work was provided by Ms. Denise S. Ponchak, NASA Lewis Research Center, and Dr. Albert R. Miller, NASA Headquarters, Office of Space Communications.

TABLE OF CONTENTS

Page

PREFACE i

ACKNOWLEDGMENT ii

LIST OF FIGURES iv

FOREWORD v

CHAPTER 1 TERRESTRIAL TELECOMMUNICATIONS SERVICES TECHNOLOGY TRENDS 1-1

SUMMARY 1-1

1. INTRODUCTION 1-2

2. LONG-RANGE TECHNOLOGY TRENDS 1-3

2.1 ANALYSIS OF TRENDS 1-3
2.2 FUTURE APPLICATIONS 1-15
2.3 EMERGING TECHNOLOGIES 1-17

3. RESULTS 1-31

3.1 IMPACT OF TERRESTRIAL TELECOMMUNICATIONS SERVICES TECHNOLOGY ON NASA 1-31
3.2 TECHNOLOGY ROADMAP 1-34
3.3 FEASIBILITY AND RISK 1-34

CHAPTER 2 MOBILE SATELLITE SERVICE TECHNOLOGY TRENDS 2-1

SUMMARY 2-1

1. INTRODUCTION 2-1

2. LONG RANGE TECHNOLOGY TRENDS 2-2

2.1 ANALYSIS OF TRENDS 2-2
2.2 FUTURE APPLICATIONS 2-11
2.3 EMERGING TECHNOLOGIES 2-12

3. RESULTS 2-14

3.1 IMPACT OF MOBILE SATELLITE SERVICE TECHNOLOGY ON NASA 2-14
3.2 TECHNOLOGY ROADMAP 2-15
3.3 FEASIBILITY AND RISK 2-15

ANNEX 1. ACRONYMS AND ABBREVIATIONS A1-1

LIST OF FIGURES

Page

1-1 Service Rollout – A Tentative Schedule 1-9

1-2 High Performance Applications – Delay Sensitivity and Data Volume Characteristics 1-15

1-3 Number of Hosts on the Internet 1-26

1-4 Comparison of Network Capabilities 1-29

FOREWORD

The National Aeronautics and Space Administration (NASA) is a major user of communications and information systems technology. NASA requirements are growing rapidly as missions and scientific instruments become more complex and data processing intensive. NASA information systems typically have long life cycles not only because of the nature of the science missions and the realities of the funding process, but because missions are delayed or expected lifetimes are exceeded. Systems development is complicated by the fast pace of technological change, exemplified by the doubling in performance of microprocessors as quickly as every 18 months, popularly referred to as Moore's Law. Systems may become obsolete early in the life cycle, unless the capability to upgrade is designed in from the beginning. Waiting, for example, 10 years to upgrade a system because of budget constraints may no longer be affordable, since the changes in technology may make it nearly impossible to salvage existing software, which is a major investment cost. In order to be able to plan for upgrades to major systems, data are needed to project the future performance levels of communications and data processing systems and related components. Ultimately, such data may be used to build a model for technological change that would allow planners to make informed estimates of system cost many years in advance. This information would permit the immediate insertion of new technology while it is still state of the art.

NASA's Office of Space Communications (OSC) is tasked to conduct this planning process to meet NASA's science mission and other communications and data processing requirements. A set of technology trend studies was undertaken by Science Applications International Corporation (SAIC) for OSC to identify quantitative data that can be used to predict performance of electronic equipment in the future to assist in the planning process. Only commercially available, off-the-shelf technology was included. For each technology area considered, the current state of the technology is discussed, future applications that could benefit from use of the technology are identified, and likely future developments of the technology are described. The impact of each technology area on NASA operations is presented together with a discussion of the feasibility and risk associated with its development. An approximate timeline is given for the next 15 to 25 years to indicate the anticipated evolution of capabilities within each of the technology areas considered. The steep rate of change projected in some technology areas underscores the need for such data for the purpose of planning information systems. Another beneficial result of the data collection effort is the insight it provides to areas where breakthroughs are likely to occur in key technologies.

The study findings are organized into separate volumes. Volume I consists of four chapters: two chapters devoted to computers at the physical and system levels, respectively, and one chapter each devoted to data storage and photonics technologies. Volume II also contains four chapters: one each on technology trends for database systems, computer software, neural and fuzzy systems, and artificial intelligence. This volume, Volume III, contains two chapters: one on technology-driven terrestrial telecommunications services, and one devoted to advanced mobile communications services using a variety of communications satellite systems. The principal study results are summarized at the beginning of each chapter.

CHAPTER 1. TERRESTRIAL TELECOMMUNICATIONS SERVICES TECHNOLOGY TRENDS

SUMMARY

While asynchronous transfer mode (ATM) has been widely hailed for the past year or two as the future ubiquitous transmission technology, 1996 has seen the enthusiasm cool somewhat. Now, more conservative projections point to a gradual introduction of ATM as one of a number of technological alternatives for meeting growing communication needs. Indeed, it now appears that hybrid networks, using a combination of transmission technologies, may predominate, even over the long run. Nevertheless, ATM will find wide applicability because of its many attractive characteristics, including: scalability to extremely high data rates; ability to handle the entire mix of voice, data, image, and video traffic; provision of bandwidth-on-demand; and, worldwide support through the establishment of standards and participation in the ATM Forum. ATM can be used in both local area and wide area applications and seems to have the broad support of vendors, carriers, and users.

In the near-term, a number of technologies will be popular, including frame relay, Switched Multimegabit Data Service (SMDS), and Integrated Services Digital Network (ISDN), as well as ATM. There are situations in which each is preferable based upon traffic characteristics, cost, and availability of service. The development of interoperability specifications between these various technologies will help to ensure that devices using one technology will be able to communicate with those using a different one.

The demand for increased bandwidth will continue to grow as a result of increased transmission of large data files, imagery, video and multimedia applications, such as videoconferencing and collaborative interactive work sessions among participants at remote locations. While extremely high data rates may not be needed at the desktop, the aggregate traffic will require gigabit per second capacity in the network backbones. Growth in residential access to networks such as the Internet, and the phenomenal growth of the Internet itself also spell a need for more transmission capacity. Fortunately, available bandwidth will grow dramatically as a result of new technologies to exploit the huge capacity of fiber-optic cable. Some predictions call for a thousand-fold increase in bandwidth over the next decade.

The trend toward public networks is continuing. Many companies have given up maintaining private networks in favor of obtaining transmission capacity on an as-needed basis from commercial carriers. Customers can then benefit from the introduction of new network technologies such as frame relay, SMDS, and ATM, without having to make large capital investments.

Prices for telecommunications equipment and service will continue to fall in response to increased demand and the arrival of more competition resulting from deregulation of the industry. Opening up the local access market is expected to result in a large increase in the number of vendors and service providers offering a proliferation of new services.

The Internet will continue its explosive growth. It will be forced to examine changes to its structure to accommodate this growth. Additional backbone capacity will have to be added at considerable cost at the same time that the government is backing away from subsidizing Internet operations. The questions of who will pay and how fees will be structured need to be answered. Changes in the Internet protocols are underway to address the increased traffic and to provide additional services in response to users' needs.

The market will determine which technologies, standards, and applications will dominate in the future. Historical experience shows that standardization by committee without prior implementation experience should be avoided.

1. INTRODUCTION

The increasing demand for more bandwidth that has been reported widely in recent years, both in the technical literature and by the popular media, is continuing. This demand is fueled by interest in very data intensive services and applications, such as transmission of bit-mapped graphics, medical images, computer-aided design and manufacturing files, high-fidelity full-motion video, multimedia, and the need to interconnect local area networks (LANs). This last need is exemplified by the surging growth of the Internet, causing tremendous growth in the amount of network traffic, much of which, thanks to the popularity of the World Wide Web (WWW), consists of graphic, sound, and video files. This extra traffic demands a high capacity backbone network to prevent the increasing numbers of users from experiencing intolerably long transmission delays.

Multimedia traffic tends to be "bursty", resulting in the need for service with variable on-demand bandwidth and near-instantaneous connectivity. Multiple types of service are required to effectively support various applications and requirements. Another trend is a general downsizing within organizations, for example, a migration from proprietary mainframe to terminal network traffic to a client-server environment [SITK91]. LAN speeds are poised to transition to the newer higher rate protocols operating in the 50 to 150 megabits per second (Mbps) range. The demand for LAN interconnection over wide area networks (WANs) is booming. The need for wider bandwidth WAN services has led to the development of new packet switching technologies such as ATM, capable of handling transmission rates of hundreds of megabits per second and higher.

Satisfying the demand for more bandwidth will not pose a problem according to some industry observers, notably George Gilder [GILD94]. He feels that we are experiencing a bandwidth explosion with capacity growing at a rate that exceeds even the dizzying pace at which computing power has been growing in recent years. The latter has behaved according to the so-called Moore's Law (after Intel co-founder Gordon Moore) which states that transistor chip density, and consequently the performance-price ratio of computers, doubles every 18 months. Available bandwidth, however, will grow at rates from five to 100 times as great.

Bill Gates agrees, going so far as to state, "We'll have infinite bandwidth in a decade's time." The predicted abundance of bandwidth has interesting implications for future technology development. Whereas now much of the processing at communications nodes, such as error detection and correction and data compression, has been dictated by the limited quality and capacity of the transmission medium, in the future many of these functions will no longer be needed. Instead of needing to devote resources to communications functions, which usually entails use of specialized chips, processing power can be devoted to document management, database manipulation, simulations, or other functions to improve the quality of interactive communications.

Extremely high bandwidth can change the very nature of computing. Processing power can be distributed over wide areas with the network serving the function of the computer bus or backplane. Many functions which are now done in hardware for reasons of processing speed can again be done in software thereby freeing applications from dependence on particular hardware. Personal computers (PCs) can access databases and libraries on the other side of the world as easily as they access their own hard disk or CD-ROM. There will be less intelligence in the backbone network and more in customer premises equipment (CPE) and access networks. We will realize the slogan of Sun Microsystems that "the network is the computer" [GUID95].

An indication of the surge in commercially available bandwidth is provided by MCI. In 1994 they offered a 2.4 gigabits per second (Gbps) fiber connection to corporate customers. By the end of 1996 the capacity of the same link is scheduled to rise to 40 Gbps [GILD94]. On the research front, during 1994 a group at AT&T Bell Laboratories, using erbium-doped amplifiers, achieved multi-mode optical transmission rates of 340 Gbps (as seventeen 20 Gbps channels) over 150 kilometers (km) with repeaters spaced at 50 km intervals [KOBB95].

ATM is emerging as the dominant transmission technology to achieve high data rates. It takes advantage of the high-quality, low-noise transmission media available today, notably optical fiber. ATM uses a streamlined stripped-down protocol without error correction capability. As a result of the simplified structure, ATM cells can be switched rapidly using hardware-based switches. ATM switches from such companies as Fujitsu, AT&T, Fore Systems, and SynOptics will soon be able to switch ATM cells at up to 2.4 Gbps. Bell Northern Research is investigating techniques to permit building optical switches with capacities in excess of one terabit per second (Tbps). The associated architecture incorporates multiple ATM peripheral switches [NORT95].

A strong "bypass" movement—an attempt by corporations to procure WAN services at below public network rates—occurred in the 1980s. This has prompted a response from the public telecommunications service companies as they convert to an all-fiber-optics transmission capacity to provide network services at lower cost, which is more than competitive with private bypass solutions. This, coupled with the industry trend toward "out-sourcing", has started a movement back to the public networks. There are many opportunities on the horizon for technology insertion—that is, using both public and private network solutions, and low-cost commercial off-the-shelf equipment.

Below we discuss some of the existing and emerging network technologies, notably ATM, that will permit the needs for high-speed transmission of information to be met in the future. An overview of the technologies is presented, with ATM being treated in more depth. Some applications driving the need for additional bandwidth are described. The related issues of telecommunications costs, the changing regulatory environment, and the growth and expanding role of the Internet are explored. The impact of emerging technologies on the National Aeronautics and Space Administration (NASA) is discussed, including a description of possible risks, and an approximate timeline for network evolution is presented in the form of a technology road map.

NASA's challenge is to increase capability by at least an order of magnitude, while maintaining a flat budget. The sophistication of future scientific data collection systems will soon outpace the capabilities of existing information systems to collect, process, store, distribute, and manage the information collected. Information will be collected at rates exceeding the ability of users to sort, locate, and interpret data. Increasing the productivity of scientists and analysts will depend upon greater efficiency and effectiveness of the information systems they use. Efficiency can be increased by bringing data closer to the user in an efficient manner. The key is networking and communications. Client-server processing is changing the way in which applications cooperate. Rather than creating communications channels between processes, the exchange of service requests is preferred [LESN90, MILL87].

2. LONG-RANGE TECHNOLOGY TRENDS

2.1 ANALYSIS OF TRENDS

2.1.1 Local Area Networks

The transition from systems based on centralized mainframes to more distributed architectures is changing the usage and role of networking. The establishment and maintenance of connections between network nodes now falls upon the network. More and more complex applications are migrating to the workstation which in turn makes use of services from the network (e.g., algorithm computations, file service, and query service). Applications will execute through use of multi-tasking operating systems such as UNIX. Central processor unit (CPU) speeds and memory capacity have been growing exponentially in recent years. Storage capacity also has expanded exponentially, with access rates only improving at a slower logarithmic rate. Gigabit local storage will be possible through multi-head and multi-platter magnetic and optical techniques. High-end networks, such as fiber distributed data interface (FDDI) and the high performance parallel interface (HIPPI) will become more common as building blocks of tomorrow's networks if market obstacles can be overcome.

Ethernet and Token Ring were in wide use in the mid-to-late 1980s. At first, single isolated LANs were the norm. As interconnect technology (routers and bridges) developed, LANs interconnected, usually with a single or multiple backbone LAN. As 1990 approached, organizations were faced with an overload of LAN backbones as an increasing number of LANs were interconnected. FDDI was first introduced into modern LAN systems as a higher performance LAN at 100 Mbps for interconnection among bridges and routers. Workstations evolved to higher performance levels with advances in reduced instruction set computer (RISC) architectures and faster memory and disk drive technologies, so networks became constrained by LAN performance levels again. FDDI is moving to the desktop to solve this problem. It is anticipated that a follow-on to FDDI will be needed in the future, first as a backbone LAN and later as a higher performance workstation attachment LAN [FINK92].

Fiber Distributed Data Interface

FDDI is a high-speed data service connecting subscriber LANs in a metropolitan area, usually over a shared 100 Mbps fiber backbone, but now also available over twisted pair cable (see below). Connection to the backbone is at standard Ethernet or Token Ring LAN speeds (4 or 16 Mbps for 802.5 Token Ring, or 10 Mbps for 802.3 Ethernet). FDDI eliminates the need for routing equipment. The span of the network is limited to central offices in a specific geographical area; network span is up to about 200 km, with up to 2 km between nodes. FDDI topology uses dual rings for enhanced reliability [BARL92]. The main obstacle to widespread deployment is the high per-station cost because of the fiber-optic hardware. Costs are expected to decrease as FDDI shipments increase and more vendors enter the market.

It is possible to extend the reach of FDDI networks by connecting individual FDDI LANs through bridges and routers. Bell Atlantic has implemented such a service, FDDI Network Service, in the Washington, DC area. Achieved by interconnecting a number of central offices, this network has the potential to operate over 12,000 miles of single mode fiber [BELL95].

FDDI-II is an enhancement that adds the ability to send multimedia images over FDDI by providing circuit-switched services or isochronous transmissions. The actual FDDI-II protocol is a hybrid, providing fixed-length cells that can be reserved for circuit switching multiplexers used by isochronous services. The technique provides for the carrying of multiple streams of traffic simultaneously on the dual rings of a FDDI LAN, but allows unassigned cells to be allocated for packet use [WOLT91]. Despite the added capabilities provided by FDDI-II, little interest by industry has been shown for this technology. Multimedia capabilities can be better provided by ATM, for example.

Shielded twisted pair (STP) distributed data interface (SDDI) is a new version of the FDDI high-speed LAN standard that permits 100 Mbps transmission over copper wire. Companies such as National Semiconductor Corp., Advanced Micro Devices Inc., and network vendors Chipcom and SynOptics Communications Inc. hope to capitalize on the installed base of STP wiring, estimated at 17 million offices worldwide. SDDI connections are less costly than FDDI. SDDI supports cable lengths of up to 100 meters. It does not require line encoding to meet FDDI standards for distance and signal integrity. There is also great interest in unshielded twisted pair [VIOL92].

FDDI is competing with ATM for internetworking of LANs and WANs. ATM proponents say that FDDI is handicapped by its limited bandwidth, while backers of FDDI claim that its technology is well understood and its pricing is stable. As these two technologies struggle for dominance in the marketplace over the next few years, one likely outcome is the emergence of an ATM backbone network with FDDI LANs connected to this backbone.

Distributed Queue Dual Bus (DQDB)

DQDB is a dual Token Ring network that works over tens of kilometers or more, with nodes connected to two optical fibers for each direction. It was developed by the University of Western Australia in the mid-to-late 1980s. It has been standardized as Institute of Electrical and Electronic Engineers (IEEE) 802.6 and was designed to achieve rates of 600 Mbps. It provides all stations on the dual bus with knowledge of frames queued at all other stations, eliminating packet collisions and dramatically improving throughput [CERF91].

High Performance Parallel Interface (HIPPI)

HIPPI is a gigabit-per-second LAN, originally designed as a channel interface among computers and collocated devices like frame buffers. HIPPI has progressed quickly toward the status of a standard due to its simple objective—i.e., simplex, high-speed, point-to-point links—although it may not achieve its full potential if limited to this objective. The current trend among vendors is to extend HIPPI using different switching technologies to construct star-topology LANs.

HIPPI is designed to operate at two speeds, 800 Mbps and 1.6 Gbps. It can run over 50-pair STP copper cable as well as over single-mode and multi-mode optical fiber. When used over a point-to-point copper transmission path, distance is limited to 50 m. However, in cascaded mode, the operating distance can be extended to 200 m over copper, 300 m over multi-mode fiber, and 10 km over single-mode fiber. Latency is 160 nanoseconds and the cost per switched port is about $2,000. Nowadays, HIPPI use is not limited to connecting supercomputers. There are several developments linking HIPPI to other LAN and WAN technologies including ATM, Fiber Channel, and the synchronous optical network (SONET.) HIPPI uses a simple signaling scheme and is protocol independent. Some recent applications include molecular modeling, animation and special effects in the movie industry, and the transmission and display of medical images. HIPPI switches are an accepted technology for LAN interconnect. In a demonstration at the Supercomputing '94 conference, full motion video was transmitted through a HIPPI switch to a high-resolution monitor with no loss of quality, at a sustained throughput exceeding 30 Mbps. Standards committees are currently working on interface standards that would permit the interconnection of HIPPI LANs with ATM WANs to provide extremely high-speed end-to-end connectivity [TOLM95].

2.1.2 Wide Area Networks

Integrated Services Digital Network

ISDN arose as an end-to-end digital extension of the telephone network, originally designed to handle digitized voice and data. It developed as an evolutionary technology and has been supported by the establishment of international standards. Since it developed from the telephone-based integrated digital network, many of the techniques developed for T1 are used in ISDN. These include 32 or 64 kilobits per second (kbps) signaling rates, transmission codes, and physical connectors. ISDN has been in development since the mid-1970s and so is more mature than other technologies discussed below. User equipment connects to the ISDN through a terminal adapter or terminal interface unit depending upon whether it is a non-ISDN or ISDN terminal.

There are two classes of ISDN service, called Basic Rate Interface (BRI) and Primary Rate Interface (PRI). BRI consists of two 64 kbps bearer channels and a 16 kbps signaling channel. PRI consists of 24 64 kbps channels, 23 of which are bearer channels and one of which serves as the signaling channel, for a total capacity of 1.544 Mbps corresponding to the T1 rate. These channels are capable of handling all types of data including voice, images, and video. ISDN is connection-oriented with each call set up and torn down through messages carried on the signaling channel.

In the United States ISDN adoption has been limited by lack of availability, expensive equipment, and limited applications. Now, however, carriers are starting to report a big boost in ISDN installations resulting from a need for more bandwidth, the existence of a greater number of ISDN-enabled applications, wider service availability (ISDN can now reach about 75 percent of lines in service.), and better prices for service and equipment. One application for this technology is as a back-up for dedicated data links. Another, in use for years, is video telephony. Today, improved compression algorithms provide acceptable images even at rates of 128 kbps which can be handled by BRI service. ISDN is also used for occasional high-speed connections, such as in telemedicine to transmit high-resolution computed axial tomography scans or magnetic resonance images to a remotely located specialist.

Remaining barriers to wider use of ISDN are: lack of knowledge of the service by many carrier personnel, the large number of service options and resulting complexity of configuration, continuing unavailability in some areas far from metropolitan centers, and some continuing equipment incompatibility problems [LEVI95]. Nevertheless, the future looks positive because the infrastructure is in place. Some experts feel that ISDN is unlikely to be displaced by emerging technologies until they are equally ubiquitous – perhaps in another decade [FRAN95, FLAN95].

Frame Relay

Frame relay is an interface standard for connecting end-user equipment to a public or private packet switching network. The software can be implemented on existing X.25 routers and packet switches. This benefit made it the most quickly adopted protocol in WAN history. It has been implemented by most LAN router makers and offered or planned for offer by all major carriers and service providers. Frame relay has a low technical risk because it uses proven technology, has low initial cost, has low switch hardware cost, and is compatible with existing customer-service-unit and data-service-unit equipment.

Frame relay is a connection-oriented service providing data rates from 56 kbps to 1.544 Mbps. It employs permanent virtual circuits (PVCs) between fixed locations, and is best suited for medium-speed, bursty, LAN interconnection applications (e.g., database queries and small to medium file transfers). Frame relay provides users with T1 access rates at lower cost than for a leased line. It provides statistical multiplexing of data, regardless of the type of protocol carried, which is attractive for bursty applications [GARC92]. Frame relay uses variable frame lengths. Some have argued that it cannot run at rates higher than 10 Mbps due to bit stuffing and high-level data-link control synchronization issues. As no standard long-distance line rates exist between T1 (1.5 Mbps) and T3 (45 Mbps), frame relay may have reached its maximum throughput at T1 [SHAR92].

Frame relay's high transmission speed results from performing very few services for the end user. Today's transmission systems have far fewer errors and problems than did the systems of the 1970s and 1980s. Advantage is taken of the improvements by eliminating many time-consuming error correction, editing, and retransmission features. Data management operations, such as providing acknowledgment (ACK) and negative acknowledgment (NAK) messages, become the responsibility of the users' equipment. However, frame relay does provide flow control and connection management, and offers the user bandwidth-on-demand through the committed information rate (CIR) mechanism. The CIR represents the average traffic the user expects to send. The carrier guarantees delivery of frames transmitted up to this rate. At higher rates, frames may be dropped during periods of network congestion, although they will be delivered if sufficient transmission capacity exists.

Frame relay is well-suited to handle multi-protocol communications. The number of customer-premises ports required can be reduced since multiple virtual connections can be established over a single access line. User connection to the frame relay network is typically through a router. In addition to handling data traffic, for which it was designed, frame relay networks are capable of carrying voice traffic and, indeed, some companies have begun to make such dual use of the network [BELL95].

The use of frame relay services has jumped dramatically from $253 million in 1994 to $800 million in 1995 and is expected to quadruple again in 1996, according to Vertical Systems Group, a consulting organization. One reason for the popularity of frame relay over faster technologies such as ATM is that frame relay can handle the speeds that most users need for their networks today while being widely available with well-defined standards [FLAN95].

There has been a slight setback in plans to introduce frame relay switched virtual circuits (SVCs). The Frame Relay Forum developed an SVC specification but failed to link it with multipoint applications of interest to its user community. As a result, solutions have to be implemented using more costly PVCs which are paid for on a continuous basis instead of the as-needed basis offered by SVCs. At present, neither the switches nor CPE support the SVC standard. It is expected that SVC frame relay service will not be available until 1996. Sprint plans to offer frame relay SVCs during the first half of 1996, while AT&T will offer them by the second half of 1996.

While developed to handle data traffic, several frame relay vendors sell access devices that combine voice, fax, and data capability. Some companies, particularly those doing business with overseas locations, have found it advantageous to carry their voice traffic over frame relay. An Alaskan company was able to cut its communications costs by $250,000 per year. To be a viable solution, a company must have a good idea of its volume of data and voice traffic to ensure acceptable quality of voice transmission.

Switched Multimegabit Data Service

SMDS is a connectionless packet switching service operating at speeds of 56 kbps to 34 Mbps. Through use of addresses, anyone with an SMDS link can transmit data to anyone else with an SMDS link. This service provides transparent bandwidth-on-demand LAN interconnection for bursty data transmission via a shared public network. SMDS is designed to span across LANs, metropolitan area networks (MANs), and WANs. SMDS operations are performed by CPE such as routers rather than by end-user equipment. The local exchange carriers (LECs) are deploying SMDS nationwide with long distance services being provided by the interexchange carriers (IXCs.) Connection to the SMDS network is through a subscriber network interface which provides the proper protocols, controls traffic, and resolves congestion. SMDS can use different physical transport mechanisms. Although based upon the MAN distributed queue dual bus standard (IEEE 802.6), it can also operate over other topologies such as a point-to-point SONET carrier [BELL95].

Applications are going to drive the SMDS market. The most important early application will be LAN-to-LAN interconnection. Other applications for SMDS are file transfer, multimedia interactive computing, and image communications. The major use in the long term will be "casual connectivity" or access to high bandwidth for bursty data. An important function will be to link communities of interest. SMDS will not replace private networks. It may be used as a secondary system when private nets get bogged down or suffer a disaster. It will be a primary network for smaller customers. Pricing is one of the most complex issues. The Regional Bell Operating Companies (RBOCs) want usage-based pricing, but some subscribers are against this because they are unable to predict costs as with flat rates. The result will be a mix of flat and usage-based pricing. SMDS service must be competitive with T1 and T3 private-line alternatives if it is to succeed.

Bellcore and the RBOCs are pushing SMDS as an elegant solution to the LAN-to-LAN interconnection problem. They are hoping to use it to combat bypassing and further proliferation of private networks. Large-scale deployment of SMDS switches is difficult and costly, and may also be risky given uncertain market acceptance. The proliferation of new technologies also complicates investment decisions.

SMDS gives the capability of a totally distributed LAN architecture with no sacrifice in performance, gives a bursty LAN a point-to-multipoint interconnection, is standardized and well-documented by Bellcore, has standard billing software, is cell-based with known delays, and can support voice. However, it has a high initial cost, since new SMDS switches will be needed in addition to any in place for voice or data services, the inherent complexity will reduce availability of equipment, and access cost may be high due to large capital investment. It faces a marketing situation similar to that of ISDN in that it is only useful if all end points can access the net—the key factor that will inhibit its acceptance.

Synchronous Optical Network/Synchronous Digital Hierarchy (SDH)

SONET/SDH is really a transport interface, not a service. It is a physical layer standard providing an optical-based carrier network characterized by synchronous operations between the network components and is suitable for providing high-speed inter-LAN links. SDH is the Consultative Committee for International Telephony and Telegraphy (CCITT) designation, while SONET is the American designation. SONET can transport all kinds of traffic through a multiplexed hierarchy of transmission speeds from 51 Mbps to 2.4 Gbps, permitting data streams of varying transmission speeds to be combined or extracted without having to break down each stream into its individual components [CERF91]. SONET provides high availability and has self-healing features in the usual dual-ring topology with which it is implemented. Since it is a worldwide standard, equipment of different vendors can be interfaced without conversion operations. SONET is more stable and experiences fewer errors than older asynchronous networks.

Connection is made to the SONET network through a service adapter or terminal multiplexer. This device takes traffic from LANs, DS1, DS3, etc. and converts it to a standard format called the synchronous transport signal. The service adapter can multiplex such signals into higher multiples of the base rate (51.84 Mbps in the United States, 155.52 Mbps in Europe), called OC-1. The SONET network topology can be a ring or point-to-point. For enhanced reliability, most networks operate as a dual ring with two optical fibers.

SONET is not designed for any particular type of application – it simply serves as the physical transport for the bit stream. Protocols, such as ATM and SMDS, riding on the physical layer deal with application-specific issues. They also handle such items as connection management, flow control, and error detection and correction. SONET will contribute to the increased demand for high-speed wide area transport by providing the physical platform for broadband network services [BLAC94].

By 2000, SONET is expected to replace today's asynchronous fiber-optic trunk network and will radically affect the delivery of new services, such as fiber-to-the-curb (FTTC) and broadband ISDN (BISDN) [RITC91].

FTTC

High-volume installations of optical fiber to the office and home will be commonplace within six to ten years. The fiber-optics market alone in 1992 was about $2.9 billion and is expected to reach $4.2 billion annually by 2000. A Bellcore study predicted that FTTC installations will increase to several million by 2000 and reach 99 percent of public networks by 2025. FTTC shared architecture (i.e., opto-electronics for several homes is shared at a curb pedestal) will be the first competitive step for fiber-to-the-home. FTTC has won out as the most cost-effective strategy for residential fiber deployment. The market will not be a boom, but will see slow, steady growth for the following reasons:

- Fiber deployment is currently economical compared to copper only in areas without connectivity, rather than as a replacement for existing copper lines.
- The technology is mature, so prices will not fall due to technical advances.
- Mass production will not ramp up enough to cause a price breakthrough for radical deployment [KARP91, KUSH91].

Public Network Growth

Estimates are that between 700,000 and 2 million LANs were in operation by 1995, encompassing about 30 million PCs and workstations, with 45 percent of the LANs interconnected. There will be a move toward public virtual services and a movement of voice services away from private nets. Figure 1-1 illustrates the changing mix of public-network services.

Although economics is one of the prime drivers for moving voice into the public network, other factors are at work as well. These factors include the move toward out-sourcing and the need to minimize investment in potentially obsolescent technology. Public services can help reduce investment and network management requirements. The benefits that customers enjoy with virtual public voice services are possible with virtual public data services.

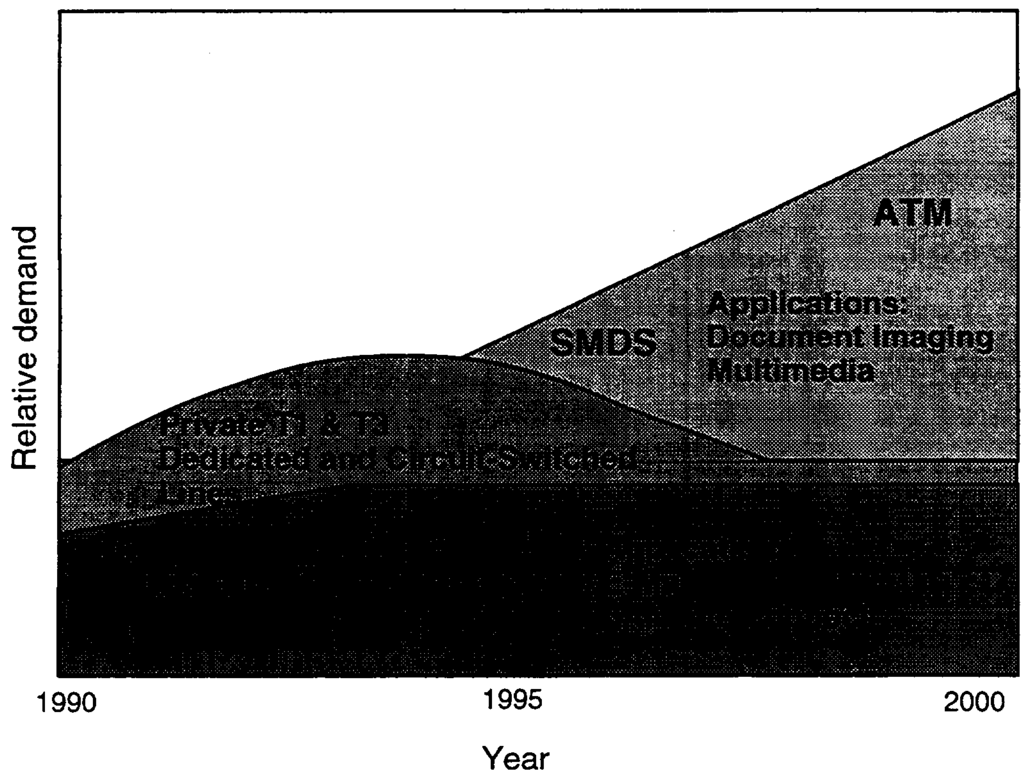

Figure 1-1. Service Rollout—A Tentative Schedule

The following service characteristics will be required of future network services:

- Large amounts of bandwidth-on-demand
- Fast connectivity to support LAN interconnection
- Usage sensitive and fixed pricing options
- Public service alternative to private nets
- Meet accepted industry standards
- Migratable to new services and technologies

- Strong network management [SITK91]

Companies are returning to the public switched digital network (PSDN) for two primary reasons: first, telephone companies and interexchange carriers (MCI, AT&T, and U.S. Sprint) are offering a wider variety of switched data services and second, tariffs are dropping. The availability of cheap access to services is spurring renewed interest in the public network. Many companies are tired of running the sideline business of maintaining private networks and are looking to PSDN to take back some of the burden. Features of the public services include the following:

- Universal access to public network services
- Transparent integration with existing applications
- Bandwidth management
- Automatic bandwidth allocation
- Time-of-day allocation
- User-interactive allocation
- Low usage costs.

In deciding between public and private network solutions, trade-off analyses between the two alternatives must be conducted by planners. In addition to the above factors, the pros and cons of public and private networks to be considered include [BRIE92]:

- Number of locations: Public networks tend to be preferred for connectivity among a large number of sites.
- Site volume: Low volume is better suited to public networks, whereas high volume makes installation of private facilities more economical.
- Equipment: With a public service, capital and maintenance costs are bypassed, and fears of obsolescence are lessened. However, with privately owned equipment, features and function can be controlled, subject to the constraints of the public carriers.
- Access: Public networks can be accessed via dial-up or dedicated facilities. Private-network facilities are dedicated.
- Staffing: Management of the network is off-loaded using public networks, but there is a certain loss of control. In the private network case, a special staff must be hired and trained to manage the network.
- Management: In a public network, there is only limited access to the carrier system for monitoring and re-configuration. Private network equipment vendors usually provide feature-rich network management systems.
- Cost: Public networks are often more economical for distributed traffic and low volume sites. They are also more efficient for centralized functionality, such as voice mail and automatic call distribution. Private networks are more economical for concentrated traffic and functionality.

Other Technologies

Here we briefly mention some alternative methods for providing increased bandwidth in the local loop to support such evolving requirements as interactive television, telecommuting applications, and access to on-line services and the Internet.

Because of the time needed to make fiber-optic cable widely available to residential users, emphasis is currently being placed on increasing the capacity of existing physical media serving private residences. One technique using existing twisted pair copper wire is called asymmetric digital subscriber line (ADSL). Current technology can achieve two Mbps transmission rates and

AT&T recently announced a new technology that will permit speeds up to six Mbps over existing copper phone lines. Moreover, standards bodies and the ADSL Forum want to boost those rates to 52 Mbps which would be able to easily map into an ATM-based broadband switching network. However, widespread implementation of such high data rates is at least five years away. While ADSL equipment now costs $2,000 to $3,000 per subscriber line, some vendors are claiming that those costs will be under $600 by the end of next year. This compares with a cost of $3,000 to $5,000 per line for optical fiber, although these costs will also decrease over time [SWEE95a].

Another technology is a hybrid fiber/coaxial cable solution. In this arrangement, optical fiber would be provided to an optical feeder node in a neighborhood with the final connection to individual residences being made using coax cable. This minimizes the amount of fiber needed and assures that the bandwidth of the fiber will be more fully utilized since it will carry the aggregate traffic of all the residences serviced by the optical feeder node. One vendor's system permits each optical node to serve up to 500 homes. These systems would be capable of providing up to three Mbps of return traffic to a cable operator's head end to be used for interactive services.

A third alternative that may find wide application in areas of lower population density, or even within areas of cities that are not wired for cable, is high-frequency wireless access, also called a wireless local loop. These systems operate in the 28 GHz frequency range to provide cellular access and interactive multimedia services. One company, CellularVision of New York, is currently providing cable services to a rapidly growing subscriber base (over 5,000 in November 1995) in a section of Brooklyn, NY. In addition to commercial licenses for New York City, the company holds licenses for test trials in Los Angeles [PHIL94, SWEE95b, IPNE96].

2.1.3 Asynchronous Transfer Mode

ATM was not discussed in either of the preceding two subsections because it can be used to support both LAN and WAN applications. It is a switching and multiplexing protocol enabling a mixture of data, voice, video, and image traffic to be carried simultaneously over a single broadband network. ATM is a connection-oriented service that combines circuit and packet switching through a random or statistical multiplexing scheme that provides the required data rate and latency for each of its constituent data streams. The individual 53-byte cells into which the data are packaged are routed to their destinations by means of address headers. ATM is able to provide high transmission rates because it performs only limited error detection and provides no retransmission services. It resides on top of the physical layer of the network so that, while SONET is the preferred means of transport, ATM can also run over DS3, FDDI, or other physical layers. The International Telecommunications Union has selected ATM running over SONET as part of their specification for broadband ISDN (BISDN) [BELL95].

The many network applications that will be facilitated by ATM include real-time video for desktop videoconferencing, video training, remote medical imaging, and simultaneous access to complex database and graphical files. ATM can also handle combinations of these activities, for example, providing video and voice of participants during a work session where documents or graphics are being viewed and changed simultaneously by the group members. Such combined activities are usually referred to as multimedia. All of the foregoing applications are characterized by the requirement for large bandwidth and low delay.

Many vendors are developing bridges, routers, and hubs that will enable customer equipment to connect to ATM networks. Because of the large installed base of existing packet networks, ATM will not replace them outright. Instead, ATM will at first be used to interconnect these existing LANs, gradually extending from the backbone to the user premises and eventually to the desktop. The pace of ATM expansion will be dictated by the time needed to standardize the interface between packet-based and cell-based networks [CLAR93].

A matrix showing the defining characteristics for some of the above technologies is presented in Table 1-1.

2.1.4 Costs

Telecommunications costs, both for equipment and services, have been falling and will continue to fall. It is impossible to know with any accuracy how far they will fall, although some experts are predicting dramatic drops. For example, George Gilder predicts, "... within seven years, as much as a tenfold drop in the real price of telephony" [GILD95].

Ultimate prices will depend on the demand and number of competitors providing the same product or service. Some anecdotal information is available on the recent rate of price reductions for particular products and services. Sprint recently cut the cost of its frame relay service. A 56/64 kbps port and economy class PVC cost $319 per month with additional PVCs costing about $33 per month. Use of frame relay service can reduce telecommunications costs of a company by up to 80 percent through the elimination of multiple local loops and multiple interexchange carrier connections in parallel. Multiple lines can be consolidated on a single T1 line using frame relay.

The costs for dedicated long-haul T1 lines have come down substantially in the past five years or so. For example, there was more than a thirty percent reduction in monthly lease costs for a 500-mile intra-state inter-local-access-and-transport-area line from 1989 to 1993. During the same period, RBOC rates for short-distance special access T1 lines fell even more dramatically, decreasing more than 80 percent for distances under six miles. A two-mile long T1 that cost $750 per month in 1989 was available in 1993 for $105. The price reductions for longer distances were more modest, but prices still fell by more than half for lines up to 100 miles in length. The reason for the greater reductions at shorter distances is probably due to competition from alternative access providers.

ISDN adoption is still somewhat hampered by relatively high prices and a multi-part pricing structure. A card to connect a PC to an ISDN line costs $599, while a device to route Ethernet traffic to Internet over ISDN is $900 for single user, $1500 for multi-user system. ISDN telephone sets cost about $500, data adapters about $1000 vs. about $100 for an analog modem. The pricing for ISDN service has three components: installation, subscription, and usage. Monthly charges range from about $25 to $100 – two to three times the rate for analog lines. Cost of service remains rather high because of the usage charge in addition to the monthly charge. The cost of using ISDN is increased further by Federal Communications Commission (FCC)-imposed subscriber line charges which are currently $3.50 per month for each channel for residential customers, and $6 per month for business customers. These charges can add 20 to 50 percent to the cost of an ISDN circuit. The FCC is examining its policy and will explore options ranging from the current system to instituting a single charge for each ISDN circuit [FRAN95].

Costs for ATM equipment have also been dropping rapidly. A network interface card that cost $4,500 in 1993 was $3,000 in 1994, and was available in April 1996 for less than $300 [VARB96]. We can expect such price reductions to continue. In one metropolitan area 45 Mbps ATM service was being offered in 1994 at a flat monthly rate of $4,500 by MFS Datanet. Sprint is offering a 45 Mbps connection between two cities on opposite coasts of the United States for about $60,000 per month [WILS94].

There are a couple of long term trends in pricing structure worth noting. As the Internet moves away from being subsidized by the government toward self-sufficiency, there is a desire on the part of the carriers to institute usage-based fees rather than the flat fees that are currently being charged. There are different ways in which this can be accomplished; for example, there could be a volume-based per-packet charge or users could pay different rates depending upon the class of priority service they wanted to ensure that messages get through even in the face of network congestion.

Table 1-1. Transmission Technology Characteristics

	FRAME RELAY	SMDS	ATM	FDDI	SONET/SDH*
New Technology?	No, uses scaled-down version of D channel link access procedure; BW on demand somewhat new	Yes, DQDB is new	Yes	FDDI-I well established; FDDI-II new and not well received	Somewhat new, synchronous networks not common
Targeted Applications	Bursty data with high capacity requirements	High speed data transfer and LAN interconnect	All; it is a multimedia technology	LAN applications; FDDI-I for data, FDDI-II for voice and data	All; application-independent
Topology dependent?	No, but current implementations are point-to-point	Yes, if physical layer of IEEE 802.6 is used; otherwise, no.	No, but current implementations are point-to-point	Yes; dual and dual ring of trees	No, but dual rings are best
Media dependent?	No, can use wire, optical fiber, etc.	No	No, can operate over wire, optical fiber, etc.	Can operate over fiber and copper; independent at physical and media access control layers	No, but higher bit rates require optical fiber
LAN/WAN based?	WAN-based; designed as high-speed LAN interconnect	Neither; supports interconnections of LANs across WANs and MANs	Either	LAN-based; provides high-speed LAN and backbone to interconnect LANs	WAN-based
Competes with	Private leased lines, X.25 networks, SMDS, ATM	Leased lines, frame relay at lower transfer rates, private networks	Private leased lines, X.25-based networks, SMDS, frame relay, high-speed LAN backbones, e.g., FDDI	ATM and lower speed LANs such as Ethernet, token ring, IEEE 802.3	Current carrier transport systems
Complements	LAN internetworking across wide areas	LAN internetworking	SONET/SDH as part of BISDN solution	Potential competitors listed above	Current carrier transport systems
Cell or frame based?	Frame-based	Cell, which is called a slot	Cell-based	Frame-based	Neither; uses concept of an envelope, (resembles a frame)
Bandwidth (BW) on demand?	Yes, with committed information rate and excess burst rate operations	Yes	Yes, within contract agreement and network BW availability	Through individual station configuration, allocation is dynamic as BW is available	No
Connection Management?	Yes, PVCs, with SVCs likely	None, connectionless	Yes, PVCs with SVCs stipulated in later releases by standards groups	FDDI-I is connectionless; yes, for FDDI-II with isochronous traffic	No
Addressing/ID scheme?	Yes, uses labels for identifying PVCs, called DLCIs	Yes, ISDN addresses	Yes, uses labels for identifying connections, which are called VCIs and VPIs	Yes, uses explicit addressing with 48-bit MAC addresses	No
Error detection and correction?	No; ACKs, NAKs, and sequencing are users' responsibility	No	Sequencing of certain traffic types, but ACKs, NAKs, and sequencing are users' responsibility	Frame check sequence checks for errors, but ACKs, NAKs, and packet sequencing are users' responsibility	No

Source: U. Black, "Emerging Communications Technologies," Prentice-Hall, Englewood Cliffs, NJ, 1994.

* SONET/SDH provides optically-based transport (physical layer); the other technologies employ higher-level protocols.

There is a movement among long-distance carriers to move from distance-sensitive to so-called "postalized" rates where the price of a telephone call would depend only on call duration and not on distance. AT&T recently received approval to offer domestic rates of 15 cents per minute during off-peak hours and 26 cents during peak hours. Sprint is offering nationwide long distance rates of ten cents per minute off-peak and 22 cents during peak hours. Both of these rate plans are available for residential subscribers only. LCI International has been offering postalized rates for more than two years and credits this pricing strategy with helping it double revenue since 1991. The Cambridge Strategic Management Group claims that such postalized rates are just a step toward ultimately having flat subscription rates for unlimited calling, which would extend to the long-distance arena a pricing scheme that is available now in the local area [LYNC95].

Whatever rate structures are used, it seems clear that prices will continue to fall so that eventually transmission costs will be almost negligible. Most carriers are realizing that they will not be able to compete and will not make money simply by transporting bits from one location to another. Transmission will be charged essentially at cost and the carriers will have to offer an array of value-added services to make a profit.

2.1.5 Regulatory Environment

This year, Congress has passed the Telecommunications Act of 1996, replacing the Communications Act of 1934 that has regulated telecommunications activity since that time. The new law will result in competition at all levels of the industry, and may bring more dramatic results than did the breakup of the Bell System in 1984. It is impossible to predict the outcome because the ground rules for conducting business will be totally different. There will undoubtedly be a somewhat chaotic period during which customers will be overwhelmed with the array of choices available to them. Prices will be wildly changing and service may be unpredictable and disjointed while companies change direction, merge, and expand to take advantage of new opportunities that emerge as regulatory constraints are removed. The two key provisions of the new legislation are:

- Long distance companies and cable TV companies can offer local voice and data service.
- Local phone companies can offer video service and long-distance voice and data service.

Some consumer groups are concerned about the timing of these provisions. They feel that until there are viable competitors who can offer local service comparable in quality to that offered by the local exchange carriers (LECs), the LECs should not be allowed to enter the long-distance arena. Also complicating the picture is the fact that many of the LECs' potential rivals – cable television operators, cellular, and personal communication system providers – are owned by the RBOCs. Advocates of the legislation claimed that deregulation will produce a flood of competitors offering a huge array of products and services, which will result in a lowering of telecommunication costs. Time will tell which view proves to be correct.

Some people are concerned that most new competitors will lack the capabilities and expertise expected by corporations, e.g., in the area of billing systems. It is difficult to establish an effective billing system that can provide the level of call-record detail needed by companies to properly charge their communication costs back to the calling party's subunit within the organization. This difficulty was demonstrated recently in the case of the Federal Telecommunications System 2000 system. This government-wide long-distance service was years behind in the development of its billing system, and the carriers involved both have long experience in billing for long-distance services: AT&T and Sprint.

The establishment of competition locally should speed the introduction of new technology into central offices and local loops as competing service providers vie for market share. For example, long distance carriers offered frame relay service several years ahead of the RBOCs.

Eventually, most service providers will offer complete packages of communication and information services. The possibility of one-stop shopping should appeal to both residential and commercial customers who do not want to go to five different places to obtain local, long distance, cable, video, and wireless services.

In general, it is felt that competition will result in more services at lower prices, though some are worried that quality may suffer. Deregulation will cause carriers to organize their business offerings around markets instead of around service classifications artificially imposed by government regulations [THYF95].

2.2 FUTURE APPLICATIONS

2.2.1 Application Requirements

The application requirements for an underlying high-performance data network include geographical distribution of nodes, the transmission of large amounts of data, and low latency (the delay between initiation of an action and the response). It is the combination of large data transfers and low latency that demands gigabit networks, for example, supercomputer networking, remote visualization, and virtual reality. Potential gigabits-per-second applications can be characterized by locating them within a delay sensitivity vs. data volume chart as shown in Figure 1-2.

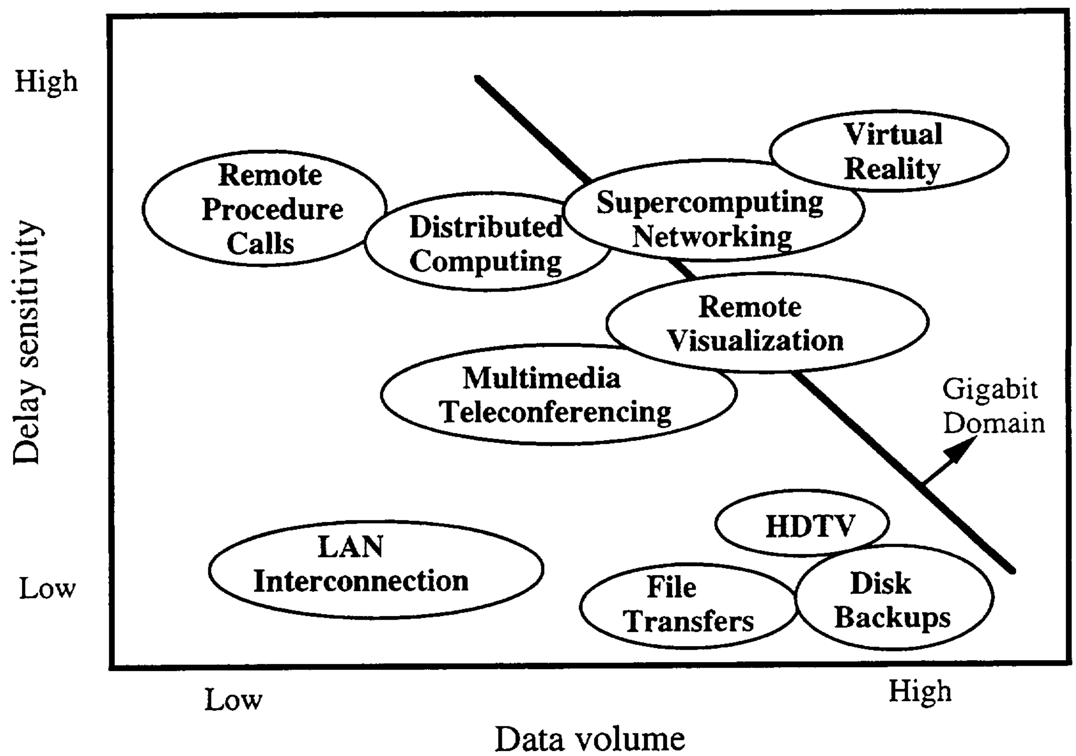

Figure 1-2. High Performance Applications — Delay Sensitivity and Data Volume Characteristics

Source: *IEEE Network Magazine,* March 1992

The increased demand for bandwidth is the result of activity in many areas, from scientific computing to increased use of telecommuting. Ironically, the bandwidth abundance that has been predicted by many will actually cause an increase in network traffic. This is because the existence of gigabit networks will allow application designers to treat computing resources at diverse locations as elements of a single system rather than viewing them as just a network of computers.

The term metacomputer has been used to refer to such a multicomputer environment where the network plays the role of a computer backplane, much the way the actual backplane or bus connects the various components (e.g., CPU, memory, storage, and display) of a single computer.

Gigabit applications can be classified as follows:

- Constrained latency services: These are necessary for human interaction (voice and video), process control, and remote sensing. This kind of information is worthless if it does not arrive within a certain time. For example, voice conversation requires immediate response between the two calling parties. There are also often constraints on latency variation (jitter).

- Transaction services: These occur in distributed systems, such as distributed operating systems, databases, or reservation systems. Examples include queries and remote procedure calls. They require low latency because the client is typically blocked while waiting for a response. This type of service is bursty in nature and requires small or moderate amounts of data to be transmitted.

- Bulk data: Large amounts of data transmitted between computers. Generally, all data must be received reliably before the receiving application can proceed, but loose latency constraints are acceptable for higher efficiency [CERF91].

2.2.2 High-Performance Network Applications

There will be an extensive use of digital image transfer in science, medicine, business, finance, government, education, and national security. Example applications are those involving high-definition 3-dimensional imaging where a user needs to interact with the image on screen or vary some parameter manually while simultaneously seeing the effects of the change. This will require the transmission of several screens per second with acceptable latencies of fractions of a second. The need for gigabit networking occurs when these images must be generated remotely.

Supercomputer centers, such as the National Center for Supercomputer Applications (NCSA) in Illinois, will be pioneers in the use of gigabit networks. Computing-intensive scientific applications include fluid dynamics computations arising from meteorological and oceanic studies, molecular chemistry, coupling a distant radio astronomy antenna array to the local supercomputer, and remote seismic array access. One atmospheric-oceanic model run by scientists at UCLA uses two supercomputers, one for each region, with the need to communicate boundary conditions between the two models. In order to achieve the benefit of using two machines, this information needs to be transmitted at a rate of at least one Gbps to avoid slowing the computations by requiring the processors to wait for the needed data.

A major new enabling technology is the multimedia digital library with a gigabit network to access it. Data storage for global climate models, for example, will be measured in terabytes. NCSA is developing such a library. Another major scientific application is data navigation, of which example data sets include the Earth Observing System (EOS) databases, distributed atmospheric visualization, earth crust multi-database integration and imaging, and terrain navigation using on-line satellite imagery. Indeed, the collection, analysis, and distribution of the massive amounts of projected EOS data has direct relevance to NASA. This will be discussed below in the subsection on impacts to NASA of evolving technologies.

A medical application is real-time planning of X-ray dosing requirements. Three-dimensional models are needed to compute the best path and intensity to deliver a toxic dose of X-rays to the cancerous area of the patient while causing minimal damage to healthy cells in the X-ray path. Faithful rendering of a diagnostic X-ray may require a 4,096-by-4,096 pixel display with 16 bits of gray scale requiring 256 megabits. A typical set of diagnostic X-rays involves 10 to 50 images, which amounts to between 2 and 10 gigabits of information. Since the computer needed to plan the dosing will likely be located away from the room where the therapy is being carried out, a high-speed transmission medium is needed to link the X-ray equipment with the computer [CATL92]. Image transmission must be done in a few seconds. While compression techniques can be employed, physicians are reluctant to make diagnoses from compressed images. As the health care industry becomes more decentralized, the need for digital storage technology and public gigabit networks will increase.

In the business arena, increased demand will result from multimedia applications, such as the combination of videoconferencing with interactive editing of documents and sharing of imagery among individuals at a number of diverse locations. In addition, sending video clips, such as Quick-Time movies, and sound files requires high transmission rates to deliver this information without delays that will be considered excessive by the end user.

Another factor that will cause an increase in demand for bandwidth is the growing popularity of telecommuting. Using portable computers, cellular phones, and fax machines, salesmen, for example, can often work out of their homes and cars without the need for an office. Companies adopting this mode of operation provide shared office space or cubicles that are assigned to workers who come into the office on an as-needed basis, much the way hotel rooms are rented. While the bandwidth required by individual workers is generally rather modest, the aggregate demand resulting from the increasing number of telecommuters will require telecommunications carriers to augment network capacity to handle the additional traffic.

The continued high rate of growth of the Internet will drive the expansion of data networks based on Transmission Control Protocol/Internet Protocol (TCP/IP). This expansion will be discussed in detail below in subsection 2.3.3.

The net result of the above factors on required bandwidth is impressive. In the business area alone, a survey of Fortune 500 companies conducted by the Cimi Corporation predicts that by the year 2000 the full-time bandwidth required by professional workers at those companies will increase to 27 Mbps from today's figure of 2.5 Mbps. This represents a compounded annual growth rate of 60 percent.

2.3 EMERGING TECHNOLOGIES

2.3.1 Wide Area Networks

Broadband ISDN (BISDN)

BISDN consists of ATM switching and multiplexing and the SONET physical layer protocol. It promises a common network for all information and communications services, rather than different nets for different services [RANS92]. It relies upon a cell-based technology. Since cells are fixed in length, the delay can be determined, and thus voice and video can be supported. BISDN is targeted for multimedia applications at speeds up to hundreds of megabits per second and is structured to allow operation at arbitrarily high bit rates. It is based on the SONET optical transmission standard in the U.S. It will initially support 155 Mbps (OC-3), 622 Mbps (OC-12), and 2.4 Gbps (OC-48) SDH rates with a 4.8 Gbps SDH rate to be introduced later. The infrastructure will actually support rates of up to 100 Gbps.

High-Speed Circuit Switching (HSCS)

HSCS provides dial-up digital data transmission at T1, T3, and higher rates. Pricing is based on usage. It requires several seconds of dial-up time and is not good for instantaneous access. The principal advantages to HSCS are that it uses existing network elements, that it is a very low-cost interim solution, and that provision and reconfiguring are fully automated. The principal disadvantages are that it is not good for bursty traffic and dial-up and teardown procedures waste user time and effort [CHEN92].

Fiber-in-the-Loop (FITL)

FITL refers to fiber-optic lines replacing copper in subscriber telephone loops for ordinary services now and broadband services in the future. Optical fiber cabling to individual homes is now being installed. In the U.S., fiber lines now total more than 3 million km. It is cost-competitive with RG-59 coaxial cable. Feeder portions of subscriber loops (i.e., the line from the central office to a remote terminal near homes) have been installed at reduced costs since 1982. Each carries 45 Mbps or higher. The 1989 cost of installing fiber to an individual home for "plain old telephone service" (POTS) was about double the $1,500 accepted industry objective. This cost has not dropped as rapidly as other costs in the industry. As of September, 1995, one company estimated the cost of supplying fiber to the home for ordinary telephone service at $2,050 ($1,050 for FTTC.) Other estimates range from $3,000 to $5,000 per line [SWEE95b]. For comparison, 1989 costs for copper-based telephony were $900 to $1400, and $600 to $900 for cable television coax.

Single-mode fiber has almost limitless bandwidth and is compatible with all wavelength division multiplexing (WDM) and all modulation techniques (including microwave subcarrier and analog). Single-mode fiber is free from optical interference effects due to the use of lasers as sources. An FITL architecture will be similar to the current twisted pair architecture. Light-emitting diodes (LEDs) and semiconductor lasers are being studied as sources. LEDs are more reliable, but lasers offer higher output power and frequency. Experiments in the early 1990s demonstrated that LEDs could attain 2 Gbps rates. In mid-1995 Oki Semiconductor brought to market single-mode laser diodes capable of 1.5 Gbps transmission rates at wavelengths of 1310 and 1510 nanometers for use in trunking applications [NACH95]. However, requirements are different for FITL than for long-haul networks. First, fiber distance is less, i.e., kilometers instead of tens of kilometers. Second, loop lasers thus require less power, about 100 microwatts compared to 500 microwatts for long-haul. Third, loop lasers must be more reliable at higher temperatures, 70 degrees Centigrade or higher. Long-haul lasers are thermoelectrically cooled, which requires 1 to 2 watts each. The design objective is to minimize power dissipation per subscriber to 4 to 6 watts.

In early 1996 Lucent Technologies, spurred in part by the move to fiber in the local-access loop, introduced two laser transmitters and a receiver. One of the transmitters is SONET/SDH-compatible for operation up to 650 Mbps. Because the transmitters need no thermoelectric cooling device, they take less space and power than competitive parts that require active cooling. In an effort to cut costs, vendors are also developing vertical-cavity surface-emitting lasers. These devices are difficult to make in wavelengths of 1300 and 1500 nanometers but will probably be useful in the shorter wavelengths of 800 or 850 nanometers for short-distance data communications applications [BASS96].

2.3.2 ATM

The ATM Forum outlines the benefits of ATM as follows:

- One network for all traffic.
- Enables new applications.
- Compatible with current cable plant.
- Incremental migration capability.
- Simplified network management.
- Long architectural lifetime.

For these reasons, as stated earlier, many experts are predicting that ATM is the high-speed networking technology of the future. Progress is being made in the development of key standards and prices are decreasing for ATM products and services. Through incremental changes, it will be possible to eventually have a truly end-to-end network extending from the desktop all the way to the WAN level. Through the use of virtual paths and circuits and a standard cell size, much of the required ATM switching can be done directly in hardware without software processing, thereby saving both time and money. By providing bandwidth-on-demand, or scalable bandwidth, ATM permits users to pay for high bandwidth only when they need it.

Until now, use of ATM has primarily been in the experimentation and demonstration stage. While many organizations are now beginning to move toward ATM solutions to their networking problems, it is estimated that it will be another two years before all the equipment needed for full implementation of ATM networks will be readily available. However, some organizations, such as the University of Virginia are already using ATM. The university has installed a 100 Mbps link from a computing facility into an operating room to allow surgeons to plan and simulate brain surgery. They also have installed 155 Mbps links to two hospitals on the other side of the Blue Ridge Mountains to transmit computed axial tomography scans and X-rays to trauma experts located at the university.

Today, LANs are interconnected through packet-based bridges and routers which must accommodate a range of packet sizes. While fairly simple to implement, these network components can introduce varying transmission delays which, while not a problem for data, cause difficulties for time-sensitive voice and video traffic. ATM can transmit voice and video traffic at constant bit rates thereby avoiding delays that may cause the quality of the received voice or video to be unacceptable. ATM is also scalable. That is, it can increase the bandwidth available for transmission without requiring a change in the information format. Current LANs, by contrast, do not scale easily. To provide more bandwidth, it is usually necessary to go to a different technology or architecture, such as replacing a single large Ethernet with several smaller ones linked by an FDDI backbone. Since ATM can run over different physical transmission media, it can accommodate speeds from 45 Mbps up to gigabits per second using the same cell format and cell switching technologies.

Operational Description

The ATM protocol has three layers that replace the first three layers of the familiar Open Systems Interconnection seven-layer protocol model (Physical, Data Link, and Network). The new layers are called the ATM Physical Layer, the ATM layer, and the ATM Adaptation Layer (AAL). The Physical Layer includes the physical interfaces, media, and the information rates used to transport information cells over the network. ATM can be carried on many physical layers, including the existing physical layer of other technologies. Because of this and the need for high bandwidths, a complementary relationship has formed between ATM and SONET. Since SONET has been accepted as an international standard, the association of the two technologies makes sense for achieving a worldwide multimedia capability using the public switched network.

The ATM layer defines the 53-byte cell structure consisting of 48 information bytes and a five-byte header containing channel and path information, plus flow control, payload type, and error detection information. The key information in the cell header is the virtual path identifiers (VPI) and virtual channel identifiers (VCI). This information tells the ATM switches which path and channel the cell belongs on. The use of these paths and channels is key to enabling ATM to provide high-speed, flexible service. Once these connections are established throughout the network, the cells are switched through hardware rather than software, resulting in very low latency. This allows the ATM switches to be independent of the Network Layer protocols such as Internet Protocol (IP), extended Internet Protocol (IPX), and AppleTalk.

Instead of addressing cells to individual destination devices, ATM addresses them to virtual channels and virtual paths. A virtual path is simply a grouping of a number of virtual channels. The term virtual is used because, through the use of time-division multiplexing, many channels and paths can exist simultaneously on the same physical cable. When several virtual channels are destined for the same node, they can be designated as a single virtual path. This simplifies switching, since intermediate switches only need to examine the VPI rather than individual VCIs. Only the final switch needs to look at the VCI to route the cells to the proper workstation.

Virtual channels are further divided into two types: permanent (PVC) and switched (SVC). PVCs require manual intervention to be set up, being pre-configured by an administration function. In this way, they are similar to static routes in packet-based networks. SVCs are dynamically created through a signaling protocol that requests that connections be set up and torn down. The use of SVCs permits ATM networks to operate much like today's LANs. While PVCs can be used with WANs, the frequency of LAN changes requires the use of SVCs. Since PVCs are much easier to specify and implement, the original ATM Forum standard specified only this type of circuit. At a later time they will address standards for SVCs. (See the following subsection for a description of an initial limited SVC standard for static networks.)

Finally, the AAL provides the link between the ATM cell and higher layer services, such as SMDS. It prepares higher layer data for conversion to cells and then segments the data into 53-byte cells. At the receiving end, the AAL recombines the cells to reconstitute the higher level data. Since ATM is capable of carrying voice, video, and data, four classes of AAL have been developed to handle traffic according to bit-rate (constant or variable) and timing (critical or not) requirements. For example, real-time video signals use AAL 1 since they require a constant bit rate and timing is critical.

Interoperability and Standards

Since ATM is intended to function over the public switched network worldwide, it is important to insure interoperability across networks. Several organizations are involved in development of ATM standards that will facilitate the required interoperability. The Technical Committee of the International Telecommunications Union (ITU-T) has developed relevant standards, mostly in its I series of recommendations for BISDN. The Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Institute (ANSI) also promulgate standards. Since these deliberative bodies often take years to reach consensus on standards, a group of vendors felt it necessary to agree more quickly on common interfaces so that their products would work together. Consequently, to develop specifications for ATM, a number of companies formed the ATM Forum in 1991. Today membership exceeds 700 companies worldwide representing telecommunications and data communications vendors, carriers, service providers, and end users. The Forum defined two types of interfaces: a User-Network Interface between end stations and switches, and a Network-Network Interface between ATM switches. A number of working groups and sub-working groups were formed to deal with the various aspects of an ATM network including signaling, traffic, alternative physical media, integration with frame relay and SMDS, network management, and testing.

Several key standards were expected to be approved in late 1995. One is a LAN emulation interface standard that would allow a network running the ATM protocol to handle Ethernet and Token Ring LAN protocols. As of February 1996, this standard was scheduled for a final working group vote in April 1996, followed by presentation to the full membership [ATMF96]. In the meantime, vendors have already been offering LAN emulation products. In September 1995, Efficient Networks Inc. began shipping software to implement the ATM Forum's proposed LAN emulation standards for servers [WIRB95].

In May of 1995, the ATM Forum approved a standard that enables multi-vendor ATM switch interoperability in static networks. It permits the support of SVCs. Previously only the use of

PVCs enabled communication to take place over switches manufactured by different vendors. Now, instead of requiring that every end-to-end circuit be set up manually, only the switch-to-switch routing tables need to be configured manually. The end-to-end circuits can then be established and torn down on an as-needed basis.

During 1994, the ATM Forum approved three physical layer standards for transmission over unshielded twisted pair (UTP) copper wire. These standards cover 155 Mbps links for point-to-point communications between ATM user devices and ATM network equipment, 1.544 Mbps (DS1) links constituting the user-to-network interface, and a sub-100 Mbps to 155 Mbps universal test and operation physical interface for ATM.

Another standard established in 1994 allows the interoperability of SMDS and ATM. It will permit users with SMDS at one site to send traffic to carrier ATM networks or to another site running ATM. Several vendors already offer CPE with the SMDS-to-ATM capability. At present, the SMDS traffic has to use a designated port on the user-to-network interface to enter the ATM network. A future standard will define the translation of SMDS cells to ATM cells to achieve true interworking. The present scheme defines SMDS as a connectionless protocol riding over an ATM transmission medium [GARE94].

The Frame Relay Forum and the ATM Forum have approved a new standard that will allow frame relay and ATM to be used in the same network without the need for the customer to do any protocol conversion. This will allow the interconnection of sites operating at relatively low speeds using frame relay with data-intensive sites using high-speed ATM. Companies will now have the option of using ATM where it is needed without incurring the expense of installing it everywhere. This capability will permit the gradual introduction of ATM as organizations evolve toward an all-ATM configuration in the future. AT&T began offering ATM-to-frame-relay interworking in December 1995 and Prudential was testing the service in January 1996. Sprint has been offering the service since November 1995. MCI Communications Corp. and LDDS WorldCom have said they will offer the capability in the first half of 1996 [REND95, REND96].

Prices

Most organizations are waiting for prices to come down before committing to ATM. Of course, prices will not start to rapidly decrease until there is sufficient demand. The price structure for ATM services now varies greatly from one provider to another. However, price decreases are anticipated. MCI has promised to institute usage-based pricing in 1995. Also, there were estimates that by the end of 1995 the price of a 155 Mbps adapter card would drop from more than $1,000 to $500 or less. In April 1996, ATM Inc. announced an ATM interface card for between $200 and $300 [VARB96].

Because of its newness, most carriers currently offer ATM services on a case-by-case basis using four classes of service. Class A is designed for voice and offers the reliability of a private-line connection. Class B is suited for video, while Classes C and D are for data. Prices for these different services can vary widely, which does not please customers. In an attempt at uniform pricing, MFS Datanet Inc. offers a flat monthly rate of $4,500 per site within a metropolitan area served by its 45 Mbps ATM network. Likewise, Sprint has published two examples of pricing for wide-area ATM: a three-node 45 Mbps connection between San Francisco, CA, Atlanta, GA, and Chicago, IL costs between $55,000 and $75,000 per month, while a connection between Seattle, WA and Miami, FL costs between $51,000 and $62,000 per month [WILS94]. More recently, a 10 Mbps connection between Orlando, FL and Burbank, CA cost one company $35,000 per month [CARU96].

Hybrid Systems

Because of the attendant expense and effort, adoption of a new technology is generally difficult if it requires that existing equipment be replaced all at once. One of the attractive features of ATM mentioned earlier is that it permits gradual migration to an all-ATM network. This permits an orderly phaseout of the old technology.

The existence of standards such as the SMDS-to-ATM specification and the frame relay-to-ATM interworking implementation agreement described above facilitate the implementation of hybrid systems. By transporting SMDS over ATM, users can combine their connectionless data services with the bandwidth guarantee provided by ATM circuit switching technology. Factors such as price, transmission rate, and service characteristics make SMDS, frame relay, and ATM attractive in different applications. The existence of hybrid interface specifications allow users to base their networking decisions on those factors at each location rather than having to implement a uniform solution to ensure interoperability among the various sites.

Other types of hybrid arrangements also have arisen. Several organizations have been using frame relay networks to carry voice traffic, a use that was not envisioned when frame relay was developed. Also, some private branch exchange (PBX) vendors are adding data interfaces to permit a PBX to function as a central voice, data, and video switch. The result will be a consolidation of voice and data on the same trunk, enabling users to interwork with a carrier's ATM network [PAPP95].

LAN Applications

Although designed as a WAN technology, ATM has been finding application as a LAN or LAN backbone to alleviate the increasing demand for bandwidth in the LAN environment that is outstripping even 10 Mbps Ethernet capability. Indeed, Cimi Corporation, a consulting firm, estimates that the needs of information workers for dedicated bandwidth will rise from 2.5 Mbps today to 27 Mbps by the end of the decade. This represents a 60 percent annual rate of growth. A survey by the Yankee Group found that LAN internetworking was the most important reason cited for implementing ATM, followed by networking of images, multimedia applications, and video.

Carnegie Mellon University is planning to implement a backbone ATM LAN, and as with many such applications, initially it will interconnect Ethernet clusters. Later, there will be an evolution to supporting direct ATM interfaces at workstations. Most organizations are being cautious about extending ATM to the desktop until products are developed that permit ATM to run efficiently over existing copper wiring. As mentioned above, some physical layer standards have already been approved by the ATM Forum for running ATM over unshielded twisted pair wire. Such standards should encourage the extension of ATM solutions all the way to end-user locations.

A consortium of 32 vendors, called the Desktop ATM25 Alliance, intended to introduce products in 1995 costing $750 per connection for ATM desktop multimedia applications running at 25 Mbps over copper wire. In May 1996, Fore Systems unveiled a line of ATM25 products including a workgroup switch, interface modules for existing switches, and an adapter. Prices are $271 per switched port and $295 per user connection [LACH96]. However, since the 25 Mbps speed does not come near the intrinsic ATM capabilities, critics say that it is premature, representing simply a watered down version of true ATM. Extensive adoption of ATM for LAN applications will probably not occur until standards and products are available that allow high-speed transmission over existing copper wire.

There are other issues surrounding use of ATM in a LAN environment as well. One is the way in which congestion will be handled. LAN traffic is inherently bursty and in the usual LAN architecture lost packets can be retransmitted without tying up dedicated transmission resources. ATM is connection-oriented so that if each cell discarded as a result of congestion requires the retransmission of the entire packet, throughput can decrease dramatically. Much work has been done and studies are continuing on ways to handle congestion in ATM networks. Two broad categories are proactive and reactive congestion control. In the first, no congestion will occur in the absence of transmission errors, while in the second, transmitters modify their behavior based on the observed state of the network. One attraction of using ATM in the LAN environment is compatibility with the expected wide-area ATM infrastructure. However, there are several challenges associated with designing and integrating a large-scale LAN or WAN. These include selection of physical media, interoperability of vendor equipment, support of legacy networks, and application performance requirements. In connection with this last area, it should be noted that the accurate measurement of ATM network performance is somewhat tricky. In many cases, traditional network monitoring and measuring tools cannot be used. The presence of equipment from different vendors complicates the monitoring process because the interactions between subsystems make it difficult to assess the performance of one particular subsystem. As a result, we can expect to see the development of new ATM LAN monitoring and measurement tools.

The ultimate success of ATM in LAN applications will depend on how it performs compared to competing technologies such as 100 Mbps Ethernet. New systems and applications will have to be developed to demonstrate that ATM can in fact deliver on its promises of higher quality of service than can be achieved by packet-based systems. Wider adoption of ATM will await further developments in the areas of standards, interoperability, equipment availability, and price reduction. These are temporary factors, however, and most experts still feel that over the long term ATM will be adopted by most organizations because of its inherent advantages in being able to carry all types of traffic [IEEE95, WILS95, PERI95].

Demonstrations and Testbeds

Amoco is conducting an ATM Research and Industrial Enterprise Study (Aries). They built a prototype network linking Chicago, Houston, Minneapolis, Naperville, Illinois, and Tulsa, Oklahoma. They are using the network to move large files of data, interactive applications, and real-time video. They are also testing the use of their current networking protocols, TCP/IP, and Novell IPX, over ATM. In a demonstration of the network, 500 Mbyte seismic data files were sent over a NASA satellite to the Minnesota Supercomputer Center for processing and analysis. Aries is the only demonstration network that connects lines belonging to Sprint, Ameritech, and WilTel.

J.C. Penney launched a three month trial in which ATM was used to transmit large data files, full-motion video, images, and voice. Hughes Aircraft will deploy ATM on its campus backbone in Los Angeles and at the WAN level to connect several locations in California.

In 1994 NASA established a pilot ATM network using private T3 lines linking ATM switches in Cleveland, Ohio, Hampton, Virginia, and Mountain View, California and used it to demonstrate basic workstation connectivity, videoconferencing, and distance learning. Their plans called for using the network for supercomputer-based research applications and transport of IP-based production traffic as well. While the pilot used PVCs, NASA would like to extend it to include SVCs to facilitate adding other research centers to the network [CSEN94].

NASA is also involved in a multiagency high-performance networking testbed in the Washington, DC area called the Advanced Technology Demonstration Network (ATDnet). It is designed as a model for a possible future metropolitan area network. The testbed was established by the Advanced Research Projects Agency (ARPA) to enable the Department of Defense and other Federal agencies to collaborate. It will emphasize early deployment of ATM and SONET technologies. The concept calls for the interconnection of several agency sites with high-speed fiber-optic transmission media overlaid with SONET and ATM protocols. Initial deployment will be at a data rate of 2.5 Gbps (OC-48), scalable up to technology limited rates.

Besides the examples cited, there are many more high-speed networking testbeds and demonstrations employing ATM technology in operation or planned throughout the United States as well as abroad.

Satellite/Terrestrial ATM Testbeds

The advantages of ATM are attractive for use over satellite as well as terrestrial links. However, there is a need to ensure interoperability between the two regimes if an ATM traffic stream is to be carried in part over satellites. Factors that will affect ATM performance over satellite include the delay introduced by propagation time, higher noise levels compared to terrestrial media that result in transmission errors, and bandwidth limitations of the satellite. Experiments to study the effects of these factors have been performed and others are planned or underway.

During a one year period from 1994 to 1995 a series of ACTS-related experiments were carried out by researchers from JPL, NASA Lewis Research Center, and others. These experiments were designed to: (1) test the performance of spacecraft and payload systems, switching networks, and earth station performance; (2) characterize the propagation path; and, (3) serve as a testbed for mobile, fixed, and video services [SCHE96]. Applications include data transfer, telemedicine, and battlefield and other military applications. In general, the results have demonstrated the viability of satellite links for low-speed data transmission, from 64 kbps to 1.544 Mbps, and voice transmission, though at a reduced performance compared to terrestrial circuits. These performance effects are due to satellite channel characteristics, especially latency and higher bit error rates.

Emphasis in experiments is shifting to high data rates as exemplified by the ACTS Gigabit Satellite Network, a cooperative program between NASA Lewis Research Center and ARPA. ATM SONET-based services have been implemented and extensive tests run over an ACTS 348 Mbps link. Test results indicate that ATM/BISDN bit error rate requirements can be met for random errors, though more extensive testing is needed to see if burst errors can be handled adequately as well. In addition, satellites with limited bandwidth will require a lot of protocol overhead to achieve the full flexibility of mixed voice, data, and video services inherent in ATM [HODE96, GEDN96].

An experiment using TCP/IP over ATM, transmitted between NASA Lewis and Boeing Corporation over ACTS, demonstrated that, in principle, a satellite link can support a high speed TCP/IP session, and that there is no difference in performance between a satellite and a terrestrial ATM/SONET link. However, applications using open loop flow control will need much larger buffers due to latency on the satellite link [BAJA96].

In the United Kingdom, the Defence Research Agency's Open Distributed Systems group is funding a project called the Study of Issues in Linking ATM Networks via Satellite (SILAS.) Some specific questions have been proposed to assess the effects of satellite link characteristics on successful transmission of ATM over satellite. These questions include:

- Which cell transport method should be used – e.g., plesiochronous digital hierarchy or synchronous digital hierarchy?
- How does noise affect cell acquisition, synchronization maintenance, and discard rate?
- How do discarded cells affect the AAL, transport protocol, and user application?
- What type of error control should be used?
- How does delay affect the signaling protocol, AAL congestion control algorithm, and user application?
- How should satellite bandwidth be managed – e.g., fixed or demand assignment, support for broadcast and multicast?

Efforts such as those described above should ensure that the performance of ATM satellite channels will be thoroughly understood. This understanding is essential in order to develop integrated satellite/terrestrial networks capable of delivering the advantages of ATM transmission to end users.

Caveat

Despite the almost universal enthusiasm for ATM, it should be noted that there are some dissenting voices who feel that ATM is being oversold. Notable among them is Peter Keen, an international consultant in information technologies [GARD95]. He claims that his clients in large multinational corporations are not that interested in ATM. For increased bandwidth on the LAN they might turn to ATM, but for increased bandwidth on the WAN they are content to upgrade from X.25 to frame relay. In this way, the basic system architecture does not have to be changed.

Keen also feels that existing network switches represent a bottleneck and they will not be able to handle adequately ATM traffic for another five years. That is, ATM provides increased transmission rates on the links, but the current switches cannot handle the resulting onslaught of bits. Development of the next-generation switch capable of handling the higher bit rates will be prohibitively expensive for the switch manufacturers based on present levels of ATM usage, on the order of $3 to $4 billion. Therefore, higher speed switches will not be developed until the vendors feel there is sufficient demand for ATM to warrant the investment.

A further complication concerns international traffic. Because of reduced capability to perform error detection and correction, ATM, and even frame relay, require high-quality circuits. Keen claims that the circuit quality in Europe is so bad that in trials not more than five percent of the packets sent have arrived at their destination. This would result in a tremendous amount of retransmission and network congestion.

Based on these considerations and the pragmatism of corporations, Keen feels that ATM is not the panacea that many are predicting, at least not in the foreseeable future. He concludes that, "The driving force behind ATM is the vendors talking to each other. And I can tell you this: When ATM arrives, it will arrive from the vendors, who are innovation-driven, technology-driven and cost-per-bit driven. However, the big corporate users are pragmatics-driven and low-risk-driven; they can't have their networks collapse, so they're also vendor-suspicious."

Others have also cautioned that ubiquitous deployment of ATM may not be desirable. In connection with gigabit network development, a 1994 National Science Foundation (NSF)/ARPA workshop stated that, "While ATM will clearly play an important role in high performance networks, other alternatives should be explored in order to develop new paradigms for successive generations of gigabit networks" [NSF95].

A number of shortcomings of ATM surfaced at the ATM Year 96 conference. The lack of network management tools is causing concern among users, and end-to-end multimedia applications will not gain widespread acceptance until standards are in place. Another concern is that security mechanisms have not been designed into ATM; they are being handled as an afterthought. For backbone applications within organizations, ATM is facing competition from lower cost switched Ethernet [SCHN96].

Excessive hype also has resulted in some vendors trying to force ATM into applications where it is not the best solution, such as narrowband networks. At speeds of 2 Mbps and below, efficient statistical multiplexing of ATM channels cannot be accomplished, resulting in up to 30 percent of bandwidth being wasted. Users understandably become disillusioned when led to such inappropriate applications by overeager vendors, which may slow the adoption of ATM in those situations where it may offer the best solution [OWEN96].

Such concerns, coupled with competition from frame relay, which is less costly and is based on widely accepted standards, have no doubt contributed to ATM sales falling short of projections. For example, in 1995 $2.5 billion was spent on frame relay technologies compared with only $250 million for ATM. Companies wishing to introduce ATM can now choose from a growing list of ATM service providers until they are able to purchase their own equipment, which probably will not be for several years [CASS96].

In summary, while ATM was widely hailed for the past year or two as the holy grail of telecommunications, 1996 has seen the enthusiasm cool somewhat with many industry observers advising caution. This seems to be a common pattern accompanying the introduction of many new technologies. It remains to be seen who is right – the enthusiastic majority who predict the rapid ascendance of ATM, or the more conservative thinkers who see a much more gradual introduction of ATM as just another technological alternative for meeting the growing communication needs of society. Indeed, it now appears that hybrid networks may predominate, using a combination of frame relay, Ethernet, and ATM technologies.

2.3.3 Evolution of the Internet

The Internet is the global network of networks that grew out of the original packet-switched ARPA Net. It has been experiencing explosive growth in recent years. Starting with three host computers in 1969, it has grown to 3.5 million hosts today representing an estimated 30 million users worldwide. This growth is shown in Figure 1-3.

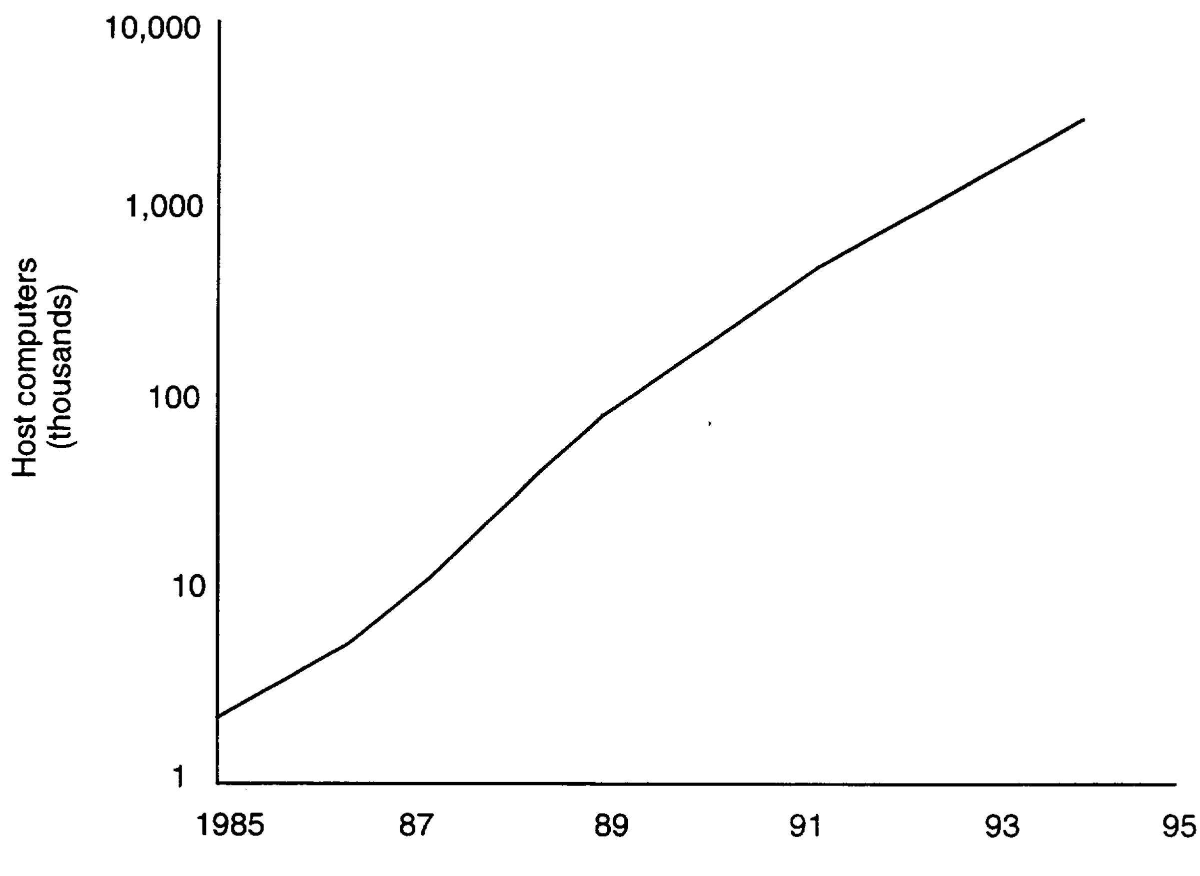

Figure 1-3. Number of Hosts on the Internet
Source: IEEE Spectrum, January 1995

In the past few years, traffic on the NSF Internet backbone has increased from one terabit per month to 18 terabits per month. Estimates of growth range from doubling each year to 15-20 percent growth per month. Commercial use of the Internet has been increasing at a rate of 30 percent quarterly. Despite this rapid growth, the potential is for even more rapid increases. While two-thirds of the Fortune 1000 companies are connected to the Internet, less than five percent of their employees use it. Only about five percent of residences have Internet access today. Because of this large untapped market, it is expected that Internet application software will proliferate rapidly.

The WWW has become the most popular application fueling Internet growth. Improvements in Web browsers will allow voice recognition, payment processing, full-motion video, and the use of intelligent agents, all of which will result in greatly increased traffic. WWW traffic is now ten percent of the total Internet backbone traffic and is the fastest growing part of the Internet [LOWE95]. Much of the growth is occurring in corporate networks hidden from view behind firewalls. Non-Web applications include sending voice and video over the Internet. There is a tremendous amount of vendor activity in this area with another dozen non-Web applications currently in development [FLAN95].

The Internet, and especially the WWW, has become a major information medium for communication, computing, learning, and business. It is a platform on which a huge variety of applications can be built. For example, MCI currently offers a broad set of services linked with teleconferencing, e-mail, and news services. They offer both dial-up and dedicated lines including access via other switching systems such as ISDN, frame relay, SMDS, and ATM. The Internet can support a wide range of applications because of its flexibility. In tests in France, for example, video was sent over the net with various frame rates, numbers of pixels, and compression ratios. The evolving Internet exemplifies the trend, mentioned elsewhere in this report, toward smart terminal devices served by a very simple, fast network.

All of this growth points to the need to expand and upgrade the present Internet so that the vastly increased traffic can be handled without the resulting congestion bringing the system to a halt. Even now, during busy periods of the day there is a noticeable, and sometimes excessive, delay in sending and receiving information over the net. The backbone network must be upgraded to T3 (45 Mbps) rates or higher. This raises the question of who will pay for the upgrades. The federal government is about to stop its subsidization of the backbone network. Commercial firms, who stand to profit from business conducted over the Internet, will probably be responsible for funding the required upgrades. While there may be some increases, the cessation of government funding is not expected to result in dramatic hikes in Internet access fees.

Some Internet access providers want to introduce usage-based pricing but users have become accustomed to and prefer a flat pricing policy. Several experts fear that a battle over pricing could split the Internet into isolated, non-communicating parts which would defeat the entire concept of global connectivity.

Besides increasing transmission speeds, other changes will be needed to accommodate the new Internet applications. Packet voice, packet video, multicasting, and multiparty conferencing require extensions to the present level of packet service available on the net. For example, some means for prioritizing packets will be needed to enable acceptable levels of video transmission under congested network conditions. To accommodate new applications, the IP is being revised. The next generation protocol – referred to as IPng or IPv6 – will offer more addressing capability and will locate addresses more rapidly. Time sensitive information will be able to find a path through the network even during conditions of congestion. For example, a video stream will be encoded as multiple channels, providing increasing levels of resolution. These channels will be successively shed as network congestion increases, resulting in a gradual degradation in the received image. The protocol will also support strong privacy and strong authentication capability [ADAM95].

Security and privacy are two important issues associated with commercialization of the Internet. These are important for financial transactions and for transmission of proprietary information. While encryption techniques exist, achieving true end-user to end-user security is a complicated issue involving human behavior as well as technology. It requires a lot of infrastructure, for example, to secure and distribute cryptographic keys and to establish registration authorities to certify the association of individuals with their cryptographic keys. The present lack of uniform security protocols, agreement on standards, certification authorities, and so on, is slowing down the Internet's achievement of its full potential.

Nearly half of the respondents to a recent survey stated that their companies suffered financial losses related to information security in the last two years, with most of the problems arising from distributed computing, particularly client-server arrangements [PANE95]. Protecting the content of World Wide Web pages is one of the most difficult security problems. To prevent tampering, a combination of firewalls and other security technologies should be used. For example, one-time passwords could be used in connection with changing the content of Web pages. Token cards are credit card-sized devices that flash a new security code every 60 seconds that is synchronized with the server. When the user logs on, he must enter the currently valid code to gain access to the server. To prevent hackers from reading or tampering with data, encryption should be used. There are also a variety of technologies to verify the identity of the server to the user or client. This would be important, for example, in a banking application so that the customer could be sure that he was in contact with his bank's server and not another posing as the bank's server.

Of course, all these security measures add both cost and complexity to the system, and they certainly are not foolproof. In two widely publicized incidents in 1995, Netscape's Web security software was shown to be vulnerable to attack. A main source of weakness is the computer operating system. For example, fraudulently posing as the root user in a Unix system provides virtually unlimited access to all files on the system. Vendors are working hard to develop security solutions for Unix, Windows NT, OS/2, and other operating systems. Although companies are beginning to pay more serious attention to security issues, some experts feel that security problems are going to get worse before they get better. One reason is the proliferation of security techniques offered by the companies providing security tools. Standardization is required to establish common authorization methods. This would then allow, for example, an electronic mall to require that a customer supply his credit card number only once for all purchases made at stores at that site. Such an arrangement will be needed to realize the full commercial potential of the Internet. More generally, it is desirable for each network user to be able to use a single user ID and password to access every platform for which he is authorized, rather than having a separate ID and password for each system [HIGG96].

With upgraded capacity, the introduction of the new IP, and the standardization of security techniques, the Internet will become even more important as a means of fostering rapid worldwide communication and information dissemination. In order to obtain the maximum benefits from using the Internet, there are several precautions that organizations can take [INFO95, HUDG95]:

- Ensure that potential Internet access providers have adequate backbone capacity and interconnectivity with other carriers.

- Seek flat-rate pricing, but be prepared for increases of those fees.

- Track regulatory changes that could affect prices and demand.

2.3.4 Advanced Network Technology

The Rainbow All-Optical Computer Networks

Dr. Paul Green of IBM is an advocate of an all-optical network, and is building a series of prototypes called Rainbow-1, -2, and -3. The premise for these networks is that gigabits-per-user applications are appearing (e.g., supercomputer visualization). Users will soon need networks that attach hundreds or thousands of nodes, each running at gigabit-per-second speeds. Current gigabit LANs, MANs, or WANs will not support these requirements because they are based on time-division principles. They share a single path across many nodes, and the front-end electronics of each node must handle all (or most) of the aggregated bit rate of the entire set of active nodes. This has been satisfactory as long as computers run at fractional-MIPS rates and terminals transmit and receive data at kilobit per second rates.

Fiber-optic links possess orders of magnitude more bandwidth than is used in today's links and nets. The traditional approach to tap this bandwidth has been to increase the time-division multiplexing bit rate, while still transmitting at essentially one wavelength. This approach has limited possibilities due to upper limits on speed achievable with electronic and photonic components and intersymbol interference introduced by chromatic dispersion on all but the shortest fiber lengths. An alternative is the all-optical network, sometimes called the passive optical network. Under this approach, WDM would be used on links and wavelength-division multiple access (WDMA) protocols would be used on networks. Electronic signal-handling would occur only at two ends of the path between nodes. The path may be topologically complex but is all-optical. A comparison of network capacity for thousands of users per link running at gigabit-per-second speeds is shown in Figure 1-4.

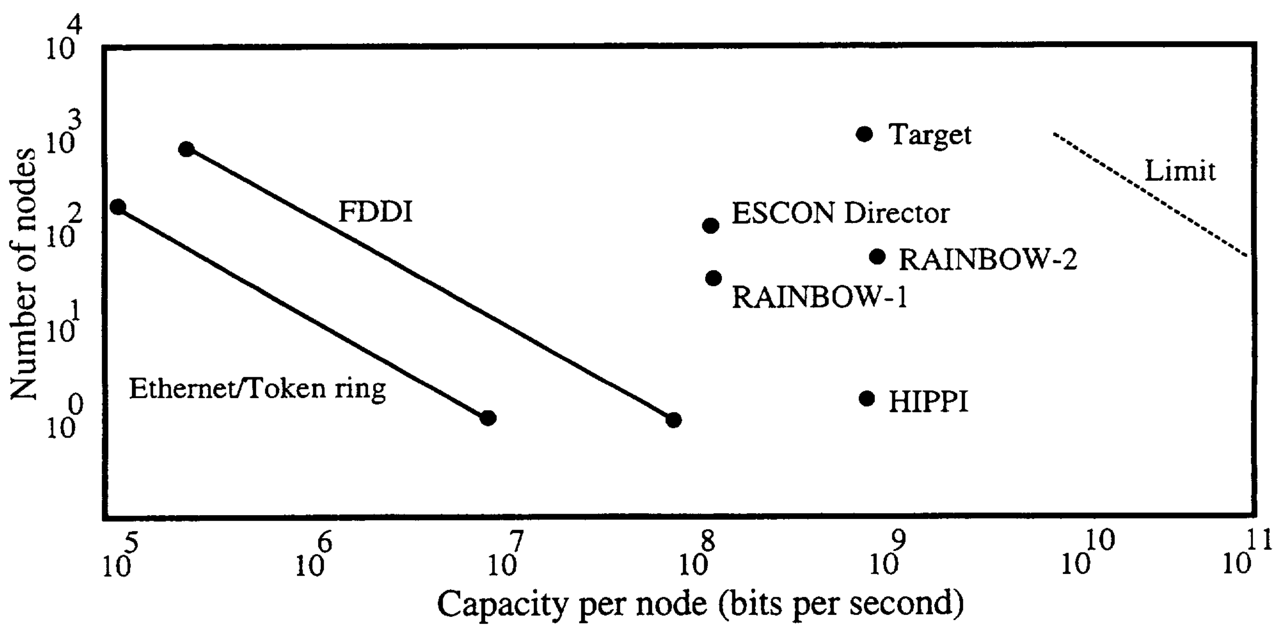

Figure 1-4. Comparison of Network Capabilities

Source: *IEEE Network Magazine,* March 1992

Using WDM, each node is assigned a different transmit wavelength. The receiver at each node must be tunable across the wavelength band occupied by the transmitters. The optical network serves as a propagation medium that broadcasts the transmitted signal to all receivers. A passive and unpowered network, it achieves great reliability and passes network control and maintenance functions to the periphery. It offers 25 terahertz (THz) bandwidth.

The results of the Telecom '91 field demonstration were that a total network throughput of 1.28 Gbps was achieved. Rainbow was intended to handle 32 nodes at 300 Mbps, or a 9.6 Gbps throughput. Some of the lessons learned were that usable all-optical networks can be built today; circuit switching is interesting, but packet switching is a must; packet switching allows many logical ports per physical port; tunable lasers promise the needed submicrosecond retuning speed, but can only tune over 7.5 nanometers of the desired 200 nanometers of bandwidth; photonic amplifiers are not a bottleneck; direct detection with filters and optical preamplifiers is a better solution than tunable coherent detection [GREE92].

Rainbow-2, a joint project between IBM and Los Alamos National Laboratory, supports up to 32 nodes running at 1 Gbps per node and was demonstrated at the Supercomputing '94 conference [IBMC96]. The objective of Rainbow-2 was to gain an understanding of supercomputer interconnection, and also to learn some of the higher level protocol implications of all-optical networking. A third generation, Rainbow-3, will add the ability to do packet switching using multi-access protocols tailored to wavelength tunable technology. The necessary sub-microsecond tuning technology is under development. Additional information about tunable optoelectronics and the Rainbow projects can be found in [GREE94].

Photonics

It is conceivable that by using the low-loss "window" of optical fibers (1,200 to 1,600 nanometers), multiple access networks carrying a total of 50 Tbps can be constructed. Fiber cannot simply be substituted for copper to upgrade capacity due to differences in photonic and electronic communications techniques. There are several problems. There is the power problem: photonic networks are power-limited, not bandwidth-limited, yielding a power-limited throughput of 10 Tbps. There is the electronic bottleneck: each LAN node must process all network traffic; thus, the total network traffic is limited to the electronic processing capacity of a single node.

Solutions to opening the electronic bottleneck include using coherent lightwave reception techniques instead of direct optical filters to obtain receiver selectivity. This type of receiver would be able to tune to select different optical channels simply by changing the frequency of a local oscillator. Another solution is using optical amplifiers to compensate for high signal attenuation and the poor energy efficiency of bus topologies.

Bell Labs extrapolates fiber-optic bandwidth from the 45 Mbps achieved in 1980 and a research limit of 350 Gbps in 1991 to predict 1,000 Gbps by 2000 [HENR89, PHOT91].

Optical Multiplexing in Fiber Networks

In spite of transmission rates exceeding 2 Gbps, current networks are exploiting less than 0.1 percent of the potential capacity of single-mode optical fiber. There are two basic ways to exploit this capacity: WDM and ultra-high bit rate transmission (100 Gbps and beyond.) This second approach uses very narrow pulses, with correspondingly wide frequency spectra, to use more efficiently the large fiber bandwidth. The very high bit rates are generated by multiplexing optical data streams directly in the optical domain. The technique is therefore known as optical time division multiplexing (OTDM). Future networks eventually are likely to incorporate both WDM and OTDM.

OTDM is still in the research phase. In a 1994 experiment, a mode-locked fiber ring laser generated a single-wavelength train of 3.5 picosecond pulses that were modulated and multiplexed to obtain a 100 Gbps pulse train. Subsequently, a 200 Gbps rate was achieved [OMAH95]. There is considerable current activity in the development of robust subsystems to work with OTDM such as optical sources and demultiplexers.

Despite this potential capacity, current optical networks are limited to data rates in the several Gbps range. For example, during the first quarter of 1996, Lucent Technologies introduced a laser module that can transmit 2.5 Gbps over each of eight wavelengths. Mitsubishi has come out with a laser diode that also operates at 2.5 Gbps and can be used for WDM in the 1,530 to 1,560 nanometers range. Mitsubishi plans to release a 10 Gbps version of the device later in 1996 [BASS96].

Gigabit Network Testbeds

Testbeds are the preferred method of determining which architecture and technology are best for gigabit networks rather than attempting to implement theoretical design of an ideal solution. In the early 1990s, The Corporation for National Research Initiatives (CNRI) with NSF and ARPA jointly sponsored six gigabit network testbeds: AURORA, BLANCA, CASA, MAGIC, NECTAR, and VISTANET. Each had some government funding but relied heavily on industry funding and university collaboration. Other testbeds have been implemented around the world as well. A list of testbed organizations has been compiled on the WWW by the National Institute for Standards and Technology [NIST96]. In addition, the reader can view a report summarizing the findings of an NSF-sponsored workshop held in July 1994 to assess the future of gigabit networking research over the succeeding five years [NSF95]. The findings reflect the experience gained from the above mentioned testbeds as well as from others with which the workshop participants were familiar. These participants felt that the testbeds provided considerable expertise in operating gigabit networks and took much of the mystery out of building such networks. They saw the eventual deployment of gigabit networks as likely, but it is not clear when such networks will be widely available. It is necessary for research programs to evolve to address the issues associated with getting gigabit networks deployed on a large scale. These issues include development of low cost transmission technology, improvements in computer operating systems and architectures, improved network security, and better programming tools. Research is also needed to develop applications optimized for implementation on gigabit networks. The most concrete recommendation called for development of a nationwide gigabit network consisting of between 20 and 50 interconnected gigabit LANs, designed to serve eventually more than 1,000 end-systems representing several thousand users.

3. RESULTS

3.1 IMPACT OF TERRESTRIAL TELECOMMUNICATIONS SERVICES TECHNOLOGY ON NASA

3.1.1 Trend Toward Public Networks

The movement back to use of the public networks for data services will increase the availability and lower the cost of high-data-rate services and thus provide opportunities for technology insertion—the use of commercial technology in government systems. For example, besides a presumed monthly cost saving, there is avoidance of investment in capital equipment that could quickly become obsolete. Capabilities can be quickly upgraded as new services become available without having to redesign the system and purchase new equipment.

The increased capabilities of new public network data services will make it necessary to do comparisons between the functionality and cost of a private network and that of a public network solution, thus complicating the planning process. The capabilities of public networks will tend to lag the private equipment market, so that for the highest data rate applications, a custom-built solution might be considered. This will require additional studies to be done. Budgeting for communications costs will be more complex when bandwidth-on-demand technologies are used. Bandwidth-on-demand is the lowest cost only if based on usage rather than on a flat rate. But usage costs are more difficult to predict and budget for.

The new public network services will also increase user expectations, in particular expectations on the part of users of NASA-generated data. Users of scientific data from spacecraft will expect interfaces at all levels, especially the user interfaces, to be compatible or identical with the those of the public network. Users may expect to be connected to real-time return links over the Internet, for example.

The transition period of the 1990s represents a continuation of the settling time of the new market regime brought about by the break up of the AT&T monopoly. During the 1990s planning will be complicated by the need to do trade-off studies and by a certain amount of confusion generated by the proliferation of new technologies. By the year 2000, it should be much clearer whether either private or public networks will dominate, or whether the market will continue to contain a mix of both.

3.1.2 Space-to-Ground Networking

The space-to-ground networking arena is also one of very dramatic change. World-wide radio frequency voice telephone networks using low Earth orbit (LEO) relay satellites are to be installed during the late 1990s. (See the accompanying chapter on Mobile Satellite Systems.) These are not expected to replace but to complement ground-based networks. However, the goal of the companies backing the LEO networks is clear—to make all telephones wireless. The ultimate impact on the rest of the industry is not yet clear. Bandwidth at radio frequencies is certainly limited compared to fiber optics. Yet this emerging technology coupled with that of wireless LANs will undoubtedly create a major trend toward universal personal computer connectivity via wireless links. This, in turn, will create a demand for wider bandwidths on the wireless networks. The first generation of space-relay networks mainly is targeted only at voice-bandwidth applications. An exception is Teledesic, which plans to provide switched, broadband connections worldwide for voice, data, videoconferencing, and interactive multimedia as early as 2002. However, it is conceivable that the second generation of such satellites, to be launched presumably sometime after 2005–2010, may have expanded bandwidth capability.

3.1.3 ATM

The long-term trend toward ATM-based networking will affect all of NASA's communications activities at both the local network and wide area network interconnection levels. Fortunately, ATM permits a gradual migration to full ATM network operation, and standards and interface specifications are being developed to allow interworking of ATM with other technologies, such as frame relay, SMDS, and ISDN. This should minimize any negative impact of the introduction of new technologies. The improvements in communications services should far outweigh the difficulties of incorporating the new technology. There will be great gains in available bandwidth with, ultimately, a single integrated desktop-to-desktop network capable of meeting the entire spectrum of communication requirements including voice, data, imagery, video, and teleconferencing.

3.1.4 NASA Telecommunications Networks

NASA currently operates two global networks, the NASA Communications (Nascom) network and the Program Support Communications Network (PSCN). Nascom is used for distribution of operational data, including command and control and telemetry, while PSCN is used to meet institutional communication needs. Both networks handle a mix of voice, data, and video traffic, including wideband data up to 50 Mbps. PSCN uses a mix of government and commercial lines and commercial, off-the-shelf hardware and systems. The emerging telecommunications technologies offer an opportunity to integrate these operational and institutional support functions into a single network incorporating the necessary reliability and security. By following the trend toward replacing private networks with use of public networks, NASA will be able to take advantage of these new technologies without having to invest heavily in new switching and transmission facilities. Additional savings should result as commercial service costs continue to drop. Furthermore, not having to maintain switches and lines will be attractive in the face of reduced manpower resulting from government downsizing. Changes in services offered and pricing structures will require a reexamination of the way in which existing and evolving requirements are satisfied to be sure that the most cost-effective options are selected consistent with maintaining maximum flexibility in the network architecture to accommodate growth and new requirements with minimum disruption in the future.

3.1.5 EOS Data Management

One networking challenge facing NASA in the near term is the need to acquire, store, and disseminate the vast amounts of data that will result from the EOS, a major component of the Mission to Planet Earth, one of NASA's five strategic enterprises for the future [VETT95]. A data and information system (EOSDIS) will manage, archive, and distribute the collected data which is expected to exceed one terabyte (10^{12} bytes) per day. EOS will consist of a series of polar-orbiting and low-inclination satellites, each carrying several sensors. These satellites will make long-term observations of Earth's atmosphere, land surface, biosphere, oceans, and polar ice. Some of the EOS data collection satellites scheduled for launch by the end of the decade and their associated data rates follow:

Satellite Series	Data Rate
EOS-AM	16.0 Mbps
EOS-PM	7.7 Mbps
EOS-CHEM	1.1 Mbps
EOS-AERO	26.0 Mbps
EOS-ALT	15.0 kbps
PEOS	3.5 Mbps

Within 15 years the database is projected to grow to ten petabytes (10^{16} bytes.) Initial estimates were that there would be several hundred primary investigators accessing these data, with about 10,000 additional global change researchers also requiring access. However, the public should also have access to the data which would expand the potential user community to the millions. The huge data volume coupled with the large number of potentially simultaneous users will require communication networks and storage devices with very high capacity.

EOS data will be stored in geographically distributed data sets known as Distributed Active Archive Centers (DAACs). Because of the large size of some data sets, users should be able to access and manipulate data without necessarily having to download files onto their systems. There will be eight DAACs which will be accessed directly by the primary researchers. The DAACs will be interconnected via dedicated high-speed communication lines, eventually running ATM (e.g., 155 Mbps OC-3 or 622 Mbps OC-12 links) and supporting bandwidth-on-demand. To facilitate access by the additional researchers, it has been proposed to add additional data providers called Public Access Resource Centers (PARCs). These centers will be connected to DAACs through the developing National Information Infrastructure, probably using the ATM protocol over BISDN. Traffic will be application dependent with, for example, agricultural applications requiring transmission rates exceeding 100 Mbps for several hundred simultaneous users. Access to data by the public at large is expected to be largely through PARCs using a wide variety of transmission media, from modems and copper lines, to hybrid systems consisting of coaxial cable, copper lines, and optical fiber, to advanced all-digital BISDN systems.

The number and diversity of potential users of EOS data underscores the importance of storage and communications standards. Movement of large volumes of data would be unnecessarily complicated by overhead associated with supporting different database management systems, image compression schemes, and transmission protocols. The need for interoperability in an undertaking as large as EOSDIS is a major concern and challenge to the information system and telecommunication network designers.

3.2 TECHNOLOGY ROADMAP

Below is an estimated timeline for the evolution of terrestrial telecommunications services over the next 25 years [SCHR94]:

1996-1998: There will be continued conversion of systems to client-server architectures and increased use of LANs, especially FDDI. Use of internetwork services on public networks also will increase. Demand will be driven by increased image data traffic. High-speed cell relay ATM switches will begin to overlay existing digital switches. They will occupy the same physical fiber trunks but will exist as logically separate networks offering new broadband services not available on the traditional narrowband digital switched network. Since ATM switching standards are still under development, the new equipment will be connected in a variety of ways.

1998-2002: There will be an increased penetration of public services to provide LAN functions as part of the public network in addition to WAN functions. Existing circuit-switched networks and ATM networks will begin to interconnect, though with limited integrated operation support systems. ATM switches will begin to handle traffic between a mix of telephones and workstations operating in a variety of modes including conventional voice and data, ISDN, and ATM. ISDN and frame relay will have key roles in this phase serving customers not needing the high bandwidth provided by ATM.

2002-2010: Optical space-to-space links will be in use . LEO satellites for fully integrated cellular telephone networking will be deployed. There will be widespread transmission of digital TV to the home over fiber cable. Continuing integration of ATM and circuit-switched networks to achieve interworking will occur. There will be integration of the service overlay and switched network operations support systems, and continued expansion of ATM switched capabilities.

2010-2020: It is possible that methods for transmitting optical signals from space to ground will be developed. Ground-based fiber-optic systems may achieve terahertz bandwidths. Full ATM operation will handle the entire spectrum of services including voice, video, data, imagery, and multimedia. Both broadband and narrowband access will be supported. Integrated management control and operations support systems will be implemented through a hierarchy of service centers supported by intelligent network elements. ATM services will be available from multiple providers including LECs, IXCs, cable operators, and competitive access providers.

3.3 FEASIBILITY AND RISK

3.3.1 Public Networks

The efforts of the public networks to recapture the data communications market from private corporate networks will increase competition and lower costs for wide area networking, providing new options or at least decreasing networking costs for NASA's OSC. However, the public network market tends to lag the requirements of organizations on the leading edge of science and technology, of which NASA is one. While preparations are under way for new commercial applications of wide-bandwidth fiber-optic networks, such as high-definition television (HDTV), it is not certain how soon these will actually be realized. Projections indicate that FTTC, a prerequisite for mass deployment of HDTV over fiber cable, will not materialize until the first decade of the 21st century. This is somewhat behind NASA's current schedule for the EOS/Space Station ramp-up.

Nevertheless, NASA can minimize the risk associated with emerging networking technologies by making use of public networks as much as possible, rather than relying on private network solutions. This would be in keeping with the general industry trend toward more reliance on public networks that has been occurring for the past several years. Indeed, NASA is already moving in this direction. In early 1994 a T1/T3 private network was replaced with SMDS. This network connects four NASA Ames Research Center contractors with NASA's Aerodynamic Simulation Program facility using SMDS running at 1.544 Mbps; a fifth contractor connects at 45 Mbps [LIND94]. Of course, in some situations it may be necessary to rely on private networks to serve specialized needs. This could occur, for example, if it became necessary to enhance network capabilities by introducing a new technology in advance of its being offered by commercial carriers, or to accommodate unique security needs.

Recognizing that the networks of the future will most likely be ATM-based should also minimize NASA's risk associated with network planning and upgrades. Being aware of emerging standards and compatibility issues will ensure a smooth evolution of networks from their present state to new configurations meeting performance requirements and achieving interoperability with other networks.

3.3.2 Internet

The Internet is rapidly growing and changing. There may be changes in pricing structure for its use and the evolving Internet protocols will support new services. The two major risk areas are in financing the maintenance and growth of the Internet and in providing security for the transmission of information. Since the government is eliminating its subsidy of the Internet, commercial users will have to pick up the cost of expanding capacity to ensure that satisfactory levels of performance are achieved. The existence of a sufficiently large pool of commercial users will depend in turn on finding workable and affordable solutions to providing adequate protection for the transmission of sensitive information over the Internet and for verifying the authenticity of both parties involved in each transaction. If these issues can be addressed successfully, NASA will be able to effectively incorporate Internet usage into its overall networking strategy.

3.3.3 Deregulation

Continued deregulation of the telecommunications industry will offer NASA and others new and improved communications services at reduced costs. The proliferation of vendors and carriers that will result, however, will no doubt produce a bewildering array of equipment and services. The various options for meeting a particular requirement will have to be carefully evaluated and compared to make an informed choice that meets the immediate need at minimum cost while preserving flexibility to accommodate changes.

3.3.4 Testbeds and Demonstrations

Performance results from various testbed and demonstration trials will point out problem areas and important issues associated with the development of new technologies. These results also will provide some indication of when the technologies might be available commercially. Many such testbed activities are currently under way, including the ATDnet in the Washington, DC area in which NASA is a participant.

If NASA wishes to accelerate the development of gigabit networks while reducing risk and cost, one course of action is to piggyback on testbed projects, including the National Research and Education Network (NREN), for example. NREN is variously seen as a communications infrastructure, a high-speed national backbone, a metacomputer, a catalyst for creativity, and the springboard for its own successor. Questions remain about the responsibility and financing of a national gigabit network in the U.S. Other open issues remaining to be resolved are technology choices, applications, economics, and politics.

By continuing to take an active part in such testbeds and experimental networks and tracking other high-speed network research activities, NASA will remain at the forefront of networking technology developments and be ideally positioned to incorporate the latest techniques in its network planning activities. This proactive approach will allow NASA to meet its telecommunication needs at minimum cost while preserving the flexibility to effectively and smoothly accommodate new requirements well into the next century.

References

[ADAM95] Adam, J.A.,"Upgrading the Internet," *IEEE Spectrum*, September 1995, vol. 32, no. 9, p. 24.

[ATMF96] ATM Forum, "ATM Forum Spec Watch – Current Work Items as of February 1996," reported on the World Wide Web at http://www.atmforum.com/atmforum/specwatch_296.html.

[BAJA96] Bajaj, S. et al., "Performance of TCP/IP over ATM on an ATM/SONET ACTS Channel," Proceedings of the 16th AIAA International Communications Satellite Systems Conference, Part I, p. 1008.

[BARL92] Barlow, J. P., "Man Plans, God Laughs," *IEEE Network*, March 1, 1992, p. 18.

[BASS96] Bassak, G., "Fiber-optic Components Set for Data Deluge," *EE Times*, April 1, 1996, p. 28.

[BELL95] Bell Atlantic, "Fast Packet Services," from the World Wide Web at http://www.bell-atl.com/federal/html/fps.htm, 1995.

[BIER92] Biersack, E. W., C. J. Cotton, D. C. Feldmeier, A. J. McAuley, and W. D. Sincoskie, "Gigabit Networking Research at Bellcore," *IEEE Network*, March 1, 1992, p. 42.

[BLAC94] Black, U., "Emerging Communications Technologies," Prentice Hall, New York, 1994.

[BOOK92] Booker, E., "Multimedia Seen as Spur to Network Growth," *Computerworld*, April 27, 1992.

[BRIE92] Briere, D., "Public or Private," *Network World*, July 20, 1992, p. 55.

[CARP92] Carpenter, B. E., L. H. Landweber, and R. Tirler, "Where Are We with Gigabits?," *IEEE Network*, March 1, 1992, p. 10.

[CARU96] Caruso, J., "Users Outline ATM Pluses, Minuses," *CommunicationsWeek,* May 20, 1996.

[CASS96] Cassidy, P., "The Network Revolution," *Datamation*, June 15, 1996.

[CATL92] Catlett, C. E., "In Search of Gigabit Applications," *IEEE Communications Magazine*, April 1992, p. 42.

[CERF91] Cerf, V. G., "Networks," *Scientific American*, September 1, 1991, p. 72.

[CHEN92] Chen, T., "Frame Relay, SMDS, and HSCS," *Telecommunications*, May 1, 1992, p. 19.

[CHEU92] Cheung, N. K., "The Infrastructure for Gigabit Computer Networks," *IEEE Communications Magazine*, April 1992, p. 60.

[CLAR93] Clark, W.J., "Understanding Asynchronous Transfer Mode," Cabletron Systems, Inc., 1993.

[CSEN94] Csenger, M., "NASA to Shuttle IP Data Via ATM," *Communications Week*, June 6, 1994, p. 23.

[DEPR92] De Prycker, M., "ATM Switching on Demand," *IEEE Network*, March 1, 1992, p. 25.

[FINK92] Fink, R. L. and F. E. Ross, "Following the FDDI," *IEEE Network*, March 1, 1992, p. 50.

[FLAN95] Flanagan, P., "The 10 Hottest Technologies in Telecommunications: A Market Research Perspective," *Telecommunications*, July 1995.

[FLEM91] Fleming, S., "Overcoming the Obstacles to BISDN," *Networking Management*, June 1991, p. 44.

[FRAN95] Frankel, D., "ISDN Reaches the Market," *IEEE Spectrum*, June 1995, page 20.

[GARC92] Garciamendez-Budar, E., "The Emergence of Frame Relay in Public Data Networks," *Telecommunications*, May 1, 1992, p. 24.

[GARD95] Gardner, D., "Keen Insights," *CommunicationsWeek*, date unknown.

[GARE94] Gareiss, *CommunicationsWeek*, May 16, 1994.

[GEDN96] Gedney, R. T. and F. Gargione, "Considerations for Satellites Providing NII/GII Integrated Services Using ACTS Results," Proceedings of the 16th AIAA International Communications Satellite Systems Conference, Part I, p. 344.

[GILD94] Gilder, G., "The Bandwidth Tidal Wave," *Forbes ASAP*, December 5, 1994, p. 163.

[GILD95] Gilder, G. and F. Gregorsky, "Republicans Flunk Tech 101," *Wall Street Journal*, July 31, 1995, p. A14.

[GREE92] Green, P. E., "An All-Optical Computer Network: Lessons Learned," *IEEE Network*, March 1, 1992, p. 56.

[GREE94] Green. P. E., "Toward Customer-Useable All-Optical Networks," IEEE Communications Magazine, December 1994, p. 44.

[GUID95] Guidoux, L., "Intelligent Solutions for Data Communication Networks," *Telecommunications*, June 1995.

[HENR89] Henry, P. S., "High-Capacity Lightwave Local Area Networks," *IEEE Communications Magazine*, October 1989, p. 20.

[HIGG96] Higgins, K. J., "Swarming Your Sites," *CommunicationsWeek*, April 6, 1996, p. 37.

[HODE96] Hoder, D. and B. Kearney, "Design and Performance of the ACTS Gigabit Satellite Network High Data-Rate Ground Station," Proceedings of the 16th AIAA International Communications Satellite Systems Conference, Part I, p. 993.

[HUDG95] Hudgins-Bonafield, C., "How Will the Internet Grow," *Network Computing*, March 1, 1995.

[HUMP90] Humphrey, D., "High Speed Communications: Can a Good Idea Be Made Better?," *Supercomputing Review*, February 1990, p. 46.

[IBMC96] IBM Corporation World Wide Web page, located at http://www.research.ibm.com/wdm/motive/roadmap.html.

[IEEE95] *IEEE Journal on Selected Areas in Communications*, vol. 13, no. 4, May 1995.

[INFO95] "The Internet: Where's it all Going?," *InformationWeek*, July 17, 1995.

[IPNE96] Excerpt from *Information Provider Newsletter*, World Wide Web page located at http://www.vipconsult.com/celv.html.

[KAPL91] Kaplan, G., "Data Communications Special Guide," *IEEE Spectrum*, August 1991.

[KARP91] Karpinski, R., "Steady Growth Seen for Fiber," *Telephony*, August 5, 1991.

[KOBB95] Kobb, B.Z., "Telecommunications," *IEEE Spectrum*, January 1995, p. 30.

[KRIS91] Krishnaswamy, P., and M. Ulema, "Developments in SMDS," *Connexions*, October 1, 1991, p. 24.

[KUNG92] Kung, H. T., "Gigabit Local Area Networks: A Systems Perspective," *IEEE Communications Magazine*, April 1992, p. 79.

[KUSH91] Kushner, C., "Bringing Fiber to the Home With a Shared Architectural Design," November 1991.

[LACH96] Lach, E., "More ATM Options for the Desktop," *CommunicationsWeek*, June 3, 1996, p. 23.

[LESN90] Lesnansky, E. and W. Turner, "High Volume Data Handling and Distribution in the EOS Era," Hughes Aircraft Company, 1990.

[LEVI95] Levitt, J., "Digital Standards: Hold the Phone," *InformationWeek*, May 15, 1995.

[LIND94] Lindstrom, *CommunicationsWeek*, January 31, 1994.

[LIPP91] Lippis, N. and J. Herman, "Widening Your Internet Horizons," *Connexions*, October 1, 1991, p. 2.

[LOWE95] Berners-Lee in Lowe, S.J., "Data Communications," *IEEE Spectrum*, January 1995, p. 26.

[LUTK91] Lutkowitz, M., "The Market for SMDS: Direction and Potential," *Communications International*, January 1991.

[LYNC95] Lynch, K., "'Postalized' Rates Stir Market," *CommunicationsWeek International*, January 16, 1995.

[MCCA92] McCarthy, S., "Internet's Evolution Becomes Computer-Era Revolution," *Washington Post*, June 1, 1992.

[MCEA92] McEachern, J. A., "Gigabit Networking on the Public Transmission Network," *IEEE Communications Magazine*, April 1992, p. 70.

[MILL87] Miller, R. B. and D. A. Nichols, "AIAA-87-2201—High Rate Data Systems," NASA, 1987.

[NACH95] Nachman, M., "Oki Laser Diodes Support Fiber/Coax Nets," *Electronic Buyers News*, July, 17, 1995, p. 25.

[NIST96] "List of Testbed Organizations," on World Wide Web at http://nii.nist.gov/testbeds.html, accessed June 1996.

[NORT95] "Breaking the Terabit Barrier," *Nortel Navigator*, 2nd quarter 1995.

[NSF95] "Report on ARPA/NSF Workshop on Research in Gigabit Networks," on World Wide Web at http://www.cise.nsf.gov/ncri/giga/craig.text, September 26, 1995.

[OMAH95] O'Mahony, M. J., "Optical Multiplexing in Fiber Networks: Progress in WDM and OTDM," *IEEE Comunications Magazine*, December 1995, p. 82.

[OWEN96] Owen, D. P., "Don't Let Hype Force ATM into Wrong Slot," *CommunicationsWeek*, July 8, 1996, p. 38.

[PANE95] Panettieri, J. C., "Security – The Good News," *InformationWeek*, November 27, 1995, p. 32.

[PAPP95] Pappalardo, D., "PBXs Moving to LAN-Voice Integration," *CommunicationsWeek*, July 3, 1995.

[PERI95] Peri, R. and L. Wilson, "LAN Users Scrambling to Unclog the Plumbing," *CommunicationsWeek International*, March 20, 1995, p. 1.

[PHIL94] Phillips, B.W., "Broadband in the Local Loop," *Telecommunications*, November 1994.

[PHOT91] "World Watch: AT&T Claims Two World Records by Generating Fastest and Shortest Laser Light Pulses," *Photonics Spectra*, February 1991, p. 34.

[RANS92] Ransom, M. N. and D. R. Spears, "Applications of Public Gigabit Networks," *IEEE Network*, March 1, 1992, p. 30.

[REND95] Rendleman, J., "Dream of Frame-Relay, ATM Tie Nears Reality," *CommunicationsWeek*, August 28, 1995.

[REND96] Rendleman, J., "Prudential Tests AT&T's Frame-Relay-to-ATM Service," *CommunicationsWeek*, January 22, 1996, p. 5.

[RITC91] Ritchie, G. R., "SONET: No Longer Just a Concept," *IEEE LTS*, November 1, 1991, p. 2.

[SCHE96] Schertler, R. J., "Summary Report on Key ACTS Experiments," Proceedings of the 16th AIAA International Communications Satellite Systems Conference, Part I, p. 738.

[SCHN96] Schnaidt, P., "ATM Works, but It's Only Version 2.0," *Network Computing*, June 15, 1996.

[SCHR94] Schriftgiesser, D., "Key Trends in Broadband Communication," *Telecommunications*, vol. 28, no. 1, January 1994, p.101.

[SHAR92] Sharer, R., "Run then Fly," *LAN Magazine*, May 1, 1992, p. 85.

[SITK91] Sitko, M., "Data Strategies for the 1990's," MCI Data Services Marketing, 1991.

[SMAL90] Smalley, E., and J. F. Donohue, "ISDN: Heavy Datacomm Users May Get Busy Signal," *Digital Review*, December 3, 1990, p. 33.

[SWEE95a] Sweeney, T., "ADSL Enhanced in Bid for Local Loop," *Communications Week International*, March 20, 1995, p. 6.

[SWEE95b] Sweeney, T., "The local loop: Place your bets," *CommunicationsWeek International*, September 18, 1995, p. 17.

[THYF95] Thyfault, M.E. and J. Gambon, "The Telecom Bill: Why It Matters," *InformationWeek*, July 17, 1995.

[TOLM95] Tolmie, D. and D. Flanagan, "HIPPI: It's not Just for Supercomputers Anymore," *Data Communications*, May 8, 1995. Also at http://www.cic-5.lanl.gov/lanp/HIPPI_Data_Communications.html.

[VARB96] "Product Watch - ATM Breakthrough," *VARBusiness*, April 15, 1996.

[VETT95] R. Vetter et al., "Accessing Earth System Science Data and Applications Through High-Bandwidth Networks," *IEEE Journal on Selected Areas in Communications*, volume 13, number 5, June 1995, p. 793.

[VIOL92] Violino, B., "The Copper Connection," *Information Week*, May 18, 1992, p. 14.

[WEXL92] Wexler, J. M., "Net Managers Mull Future of Private Corporate Backbones," *Computerworld*, April 13, 1992, p. 8.

[WILS94] Wilson, L., "Are Price Delays Costing ATM?," *InformationWeek*, September 26, 1994, p.34.

[WILS95] Wilson, L., "The Lure of ATM: common sense or nonsense?," *CommunicationsWeek*, date unknown.

[WIRB95] Wirbel, L., "LAN Emulation Software Rolls," *EE Times*, September 11, 1995, p. 104.

[WOLT91] Wolter, M. S., "ANSI X3T9.5 Update: Future FDDI Standards," *Connexions*, October 1, 1991, p. 21.

CHAPTER 2. MOBILE SATELLITE SERVICE TECHNOLOGY TRENDS

SUMMARY

In the next ten years, modern telecommunications capability will be available to more users, and the range of service offerings will be greatly extended for all users. These improvements will rely on deployment of a space-based telecommunications infrastructure that uses constellations of satellites to replace traditional land lines. Technology advances in both space and ground systems have made this new infrastructure possible.

Many innovative new service offerings are targeted to mobile users equipped with small, low-power terminals that communicate with satellites in low Earth orbit (LEO). A LEO satellite constellation must be comprised of affordable spacecraft, since several are needed for continuous coverage. Many concepts use a modern "smallsat" bus with efficient, low mass components and low transponder power. Mobile satellite system (MSS) concepts can be grouped by the type of service provided, and by the orbit altitude selected.

Packet data service providers, called "Little LEOs", operating from low orbits, will provide low cost global packet store-and-forward services, and geo-position determination for users. These systems typically are projected to cost less than $200 million to develop and deploy.

Voice telephony service providers, called "Big LEOs," each plan to install a large network of small satellites that would function as a global cellular telephone network. These systems will typically cost several billion dollars. Some of the Big LEOs have more ambitious plans for broadband services, such as video and interactive multimedia uses.

Geosynchronous (GEO) satellites are also proposed by several vendors for mobile voice grade links and high-bandwidth services. These proposals share the LEO-based concept use of modern technology, i.e., small physical dimensions and low power, and therefore represent a new class of services beyond current geosynchronous communications satellites.

Considering all three groupings, there are now proposals for at least two dozen distinct system concepts. Each identifiable service offering and market niche seems to be targeted by several competitors. Limitations on available capital for financing, spectrum allocations, and orbital slots all suggest that the consolidation of plans and withdrawal of some competitors is likely. For those that succeed with deployment, there may be a further round of shake-outs when price points for services are set by the market.

Commercial space ventures such as the MSS may strongly influence the NASA mission, by directing the evolution of that mission away from mature space technologies and large complex systems to advanced space missions involving miniaturization and machine intelligence that will facilitate access to space and reduce space mission life-cycle cost.

1. INTRODUCTION

An MSS is a telecommunications architecture that serves mobile users with a system infrastructure based on satellite links. The MSS uses in-space infrastructure elements to substitute for the traditional ground-based network, and to simultaneously expand the system's service coverage to mobile users spread over a very wide, often global, area.

Four market segments for MSS service have been identified by business planners. The first is the global business traveler (the "road warrior") who is expected to be willing to pay a premium for maintaining voice and data contact regardless of location. The second market commonly discussed is remote rural locations, many in third-world countries, that may lack a completed ground telecommunications infrastructure. A third market is "SOHO" users – Small Office/Home Office operations that require voice and data links to customers, suppliers, and headquarters locations. The final segment is high-volume data transmission from remote locations. Some observers speculate that high-volume data transmission may become the first bulk user of MSS assets.

Major initiatives by industrial consortia are underway now to design and deploy MSS services before the turn of the century. Most of these consortia are global partnerships or strategic alliances that aim to reach customers around the world. U.S. satellite builders and telecommunications companies play major, often leading, roles in most of the consortia. However, most consortia have also recognized the need to involve international business concerns in the regions or countries they intend to serve, and they appear to be soliciting active participation from international government agencies.

There are far-reaching implications for the future of telecommunications and the aerospace industry of even one successful MSS implementation. Revenue from in-space infrastructure may approach that of terrestrial systems. The availability of wireless telephone handsets that do not depend on government monopolies for their operation will put pressure on many countries to move toward free-market principles for telecommunications, and may increase the demand for American-made technology. Global data-transfer capacity will also increase to support more sophisticated network-based applications, such as software distribution. Increased demand for spacecraft hardware innovations and cost reductions are likely to impact NASA and other space organizations, bringing cost reductions in subsystems and components, and possibly savings for entire flight systems as well.

2. LONG RANGE TECHNOLOGY TRENDS

2.1 ANALYSIS OF TRENDS

The explosive growth potential of MSS services is one consequence of strong demand for new communications capability, coupled with the technology advancements to meet that demand. In the U.S. alone, cellular telephones for mobile communications have sold at a compounded growth rate of 76 percent per year for the last decade. Many emerging countries, e.g., Ghana, Mexico, Pakistan, and the Philippines, have also installed cellular systems, since cellular represents a quick, relatively inexpensive way to adopt modern mass communications technology. Global MSS services are an extension of service that meets both the growing needs of current mobile telephony users in developed countries, and the needs of developing nations to deploy modern infrastructure. Although the MSS services will cost much more than cellular telephone services, the combination of global need and ready technology is expected to produce annual increases in revenue of 10 percent or better through 2002 [LOGS95].

Advanced high-efficiency and miniaturized components for spacecraft, for ground transmission sites, and for hand-held user terminals have all contributed to reducing the costs of mobile satellite systems to make them an affordable alternative for many current and near-term applications.

The feasibility of low-cost, miniaturized communications satellites was demonstrated in the 1980s by the deployment of amateur radio satellites for packet communications, and later by demonstration projects funded by the Department of Defense and built by Defense Systems, Inc. These satellites were typically launched as piggyback payloads, but some of the more recent satellites have been flown on launch vehicles explicitly designed for commercial use, such as the Orbital Sciences Corporation's Pegasus. These satellites operate from LEO using low transmit power, with a near-omnidirectional antenna gain pattern, and use low data rate store-and-forward packet relay.

To reduce weight and cost, the flight systems are of equally simple design, often box-like in shape, with passive attitude control via gravity-gradient stabilization, few complex mechanical devices (such as, articulations or movable booms), and minimal onboard signal processing capability. This simple heritage carries over to many of the current concepts: a recent design by Orbcomm shows a flat disk only a few inches thick, which allows eight satellites to be stacked in a Pegasus payload bay.

Several commercial ventures are now seeking to exploit emerging markets that might be served by this type of packet data LEO satellite. Other new commercial consortia are pursuing the development of more complex mobile telephony systems using a LEO architecture. The logic behind the architecture is simple, but controversial. To achieve mobile personal communications using satellites, small hand-held subscriber units are needed. But to get the size and cost of the hand-held units down to the required levels, low transmit power and near-omnidirectional gain are essential, since the units must be battery powered, and can carry no more than a short whip antenna. Hence, the shorter the RF propagation path length, the better. However, not all experts agree that LEO is required to meet these objectives. The CelSat architecture, discussed later in this section, is an example of an alternative approach.

LEO is also a beneficial orbital regime for voice telephony because of the greatly reduced round trip delay compared with that of a GEO. In addition, the launch vehicles can be smaller and less expensive. Thus, risk can be spread over multiple launches, reducing insurance costs, or making self-insurance feasible for very large ventures such as Teledesic.

On the other hand, to achieve continuous coverage from LEO, a "cellular" network of multiple satellites is required. Unlike a ground-based cellular network, the "cells" (i.e., the satellite footprints) move over the earth, while the subscriber units remain relatively stationary. As each satellite passes out of view, continuous coverage is maintained by handing off the link to the next satellite. The hand-off may be simple and infrequent, as in TRW's Odyssey system, or quite often and complex, as in Motorola's IRIDIUM.

An implicit feature of most of the LEO network architectures is that global or near-global coverage can be achieved. This is fortunate, because a global market must usually be pursued to justify the high investment costs. The large number of satellites required for a LEO network, coupled with the more complex ground segment facilities means that total system costs can be very high. For example, IRIDIUM architecture is estimated to cost $3.4 billion.

There are also many proposals for mobile telephony and advanced services to be supported by satellites in geosynchronous orbit. With over 300 satellites now in orbit, this is the traditional location for any satellite that provides continuous coverage over a wide area. The advantage of the GEO location is that near-global coverage requires as few as three satellites spaced at equal intervals in equatorial orbits. GEO-based operations require few, if any, hand-offs between satellites. One disadvantage is the higher initial cost of propulsion to reach the higher altitude. Another is that the greater distance generally requires more power for uplink and downlink transmissions, which may increase the weight and power requirements of portable units. These costs motivate designers to plan for longer useful life on orbit, which drives up other flight system and payload costs For communications satellites, there is also a signal delay that is noticeable in voice conversations.

The rest of Section 2.1 lists most of the currently planned MSS projects, summarized in Table 2.1, and gives a brief description of each. Most of the systems described have yet to launch the first satellite, but all plan to initiate deployment of in-space assets before the turn of the century, with commercial service starting one to two years after first launch. It is worth noting that plans can change frequently, especially as the consortia begin to raise capital, and plan for entry into world markets. Spectrum and slot allocation limitations have encouraged some companies to submit filings that may be nothing more than place-holders. Therefore, the architecture details and service offerings described in the following paragraphs should be viewed as potentially time-sensitive, and subject to revision.

Table 2.1
Proposed MSS Service Providers

Little LEO	Big LEO	GEO	
UoSAT-3	IRIDIUM	Qualcomm	AstroLink
Orbcomm	ICO	AMSC	CyberStar
FAISAT	Globalstar	Inmarsat, Inmarsat-C	GE Americom
Starsys	Odyssey	CelSat	Millennium
	Ellipso	VoiceSpan	Echostar
	Constellation/ECCO	Galaxy/Spaceway	NetSat 28
	Teledesic		
	SATIVoD		

2.1.1 Little LEO Mobile Packet Data Services

The term "Little LEO" officially refers to the three US organizations that have received FCC licenses to operate in the frequency bands allocated to LEO packet data services. These are VITA, Orbcomm, and Starsys. Since the spectrum allocation is small (148.0 to 150.05 MHz, 137.0 to 138.0 MHz, and 400.05 to 400.15 MHz.), these organizations have made mutual agreements to cooperate in spectrum usage. Orbcomm and VITA will operate in a narrowband frequency division multiple access (FDMA) mode, while Starsys will operate a code division multiple access (CDMA) system [BREE93, RFDE92]. Service offerings are limited by low data rates and the less than "real-time" nature of store-and-forward architecture. A fourth organization, Final Analysis, Inc. (FAI), is currently in the test and demonstration stage and does not yet have an FCC license.

UoSAT-3

Volunteers In Technical Assistance (VITA) was an early pioneer of wide-area satellite store-and-forward services. VITA is a non-profit organization specializing in disaster relief communications, remote area data collection, and remote control of unattended facilities in developing countries. VITA currently uses a satellite called UoSAT-3 that was built by Surrey Satellite Technology, Ltd., and launched in 1990 as an Ariane secondary payload. This satellite, which is shared with other users, allows communication during a 15-minute window several times a day from its polar sun-synchronous orbit at 800 km. The data rate is 9600 bits per second, with 4 megabytes storage on board. Messages are stored and delivered within 12 hours. VITA had also planned to use the enhanced capability of the Gemstar-1 satellite; however, it was lost in a launch failure of the Lockheed Launch Vehicle (LLV). The LLV failure also scuttled plans by CTA, Inc. to initiate its Gemtrak service for tracking transportation asset location and utilization, using the same Gemstar-1 satellite. CTA's plans call for a full constellation of 38 satellites [VITA96a, VITA96b, SBN95].

Orbcomm

Orbcomm, a joint venture of Orbital Sciences Corp. and Teleglobe of Canada, currently has two experimental satellites of its own design in orbit, and plans a network of 26 of these "Microstar" satellites by 1997, growing to 36 for full global coverage in 1998. The final constellation will consist of 4 satellites in polar orbits, and 32 satellites (8 in each of four planes) at 45 degree inclination. All will be injected into 775 km circular orbits by the Orbital Sciences

Pegasus launch vehicle from Vandenberg AFB. Each satellite is quite small at 40 kg, and of simple design, with few deployment mechanisms and largely passive gravity-gradient stabilization. The "Eight Pak" stackable design allows Pegasus to deploy as many as eight coplanar satellites on a single launch.

The intended applications announced so far by Orbcomm are truck fleet tracking, vehicle security, automobile and marine emergency location, unattended site telemetry, electronic mail, fax transmissions, and paging. (Orbital Sciences also recently acquired Magellan Systems, maker of a line of hand-held Global Positioning System (GPS) receiver equipment.) End-to-end transmission time from one user terminal to another is estimated to be 5 seconds. The service will offer 50-byte packets several times a day. Geo-location determination, called Radio Determination Satellite Service (RDSS), will also be available, as derived from Doppler measurements. A position accuracy to within 400 meters is claimed for this service, when measuring two frequencies.

Orbcomm's mobile and hand-held units, to be priced initially at about $600, should decline to $150-300 after full deployment. Each satellite is expected to cost about $1.2 million; total system cost is estimated at $220 million. As of March 1996, Orbcomm claims that the system is fully funded, with $160 million in capital invested by the partners [AWST95, VELO95, ORBC96].

FAISAT

FAI, a small disadvantaged business, has already launched the first of two test and demonstration satellites for its FAI satellite (FAISAT) constellation of "near real-time" store-and-forward services for customers worldwide. FAI has formed a partnership with Polyot, the Russian agency responsible for the Cosmos launch vehicle. Other participating organizations include the Space Dynamics Laboratory of Logan, Utah, the Center for Space Power of Texas A&M University, and ground segment providers who have yet to be selected. Targeted applications include two-way non-voice communications, management of untended remote sites, and tracking of assets in the field.

The full FAISAT constellation consists of 26 operating spacecraft: two at 83 degrees inclination, and six in each of four planes at 66 degrees. The latter four orbits also include one spare each. All orbits are at 1,000 km circular altitude. Launches of the operational satellites are scheduled to begin in 1997, with each of the two 83-degree inclination spacecraft flown as secondary payloads on the Cosmos launcher. These spacecraft weigh 100 kg each. Beginning in 1998, one Cosmos launch annually will populate one of the 66-degree orbits with six operational and one spare spacecraft (150 kg each), with the full constellation deployment completed by 2001. First commercial service is planned for 1997. Each spacecraft is a simple gravity-gradient stabilized bus.

The total system development cost for FAISAT is projected to be $150-200 million, of which approximately half must be raised as capital. Beyond investments by the principals, FAI hopes to raise $50 million in an offering to investors in 1996. Details of the subscriber fee structure are still being defined, but the company quotes a target of $0.25 per fixed-length message. Terminal equipment, which will be supplied by the company, will cost about $100 each for volume purchases; sensors and power supplies are options. FAI is also advertising flight opportunities for small secondary payloads on each of the 30 constellation spacecraft, including the on-orbit spares. Accommodations for each payload include: up to 50 kg and 0.216 cubic meters, and up to 100 W continuous power from the bus. Onboard data storage capacity is 100 Mbytes, with downlink at 256 kbps. This capability is being advertised for scientific "payloads of opportunity," or applications requiring coordinated measurements from several locations [FAI96, FATI96].

Starsys

Starsys Global Positioning, Inc., originally a partnership between Hughes STX and North American Collection and Location by Satellite (NACLS), will now be 80 percent owned by

General Electric as of Spring 1996. Starsys plans a constellation of 24 satellites weighing under 150 kg each, that will be placed in 53 degree inclined circular orbits at about 1,000 km. Six orbit planes will each hold four spacecraft. Starsys will compete directly with Orbcomm, providing packet messaging and geo-location services through low-cost portable handsets ($200-300 is the estimated price range) operating at 2-5 watts. CDMA modulation (Starsys calls this "Spread Spectrum" Multiple Access, or SSMA) will be used for frequency sharing at 150 MHz uplink and 400 MHz downlink [LOGS95, RENS96, LENO93].

2.1.2 Big LEO Mobile Telephony Services

The so-called "Big LEO" systems are to be developed by a group of companies seeking to provide mobile telephony services from low and medium-earth orbit using various frequency bands above 1 GHz: 1610-1626.5 MHz (L-band), 2483.5-2500 MHz (S-band), 5-7 GHz (C-band) and 20-30 GHz (Ka-band). These include:

- IRIDIUM (Motorola-led consortium – Iridium, Inc.)
- ICO (Inmarsat consortium)
- Globalstar (Loral and Qualcomm)
- Odyssey Telecommunications International, Inc. (TRW and Teleglobe)
- Ellipso (Mobile Communications Holdings, Inc.)
- Constellation or ECCO (Constellation Communications, Inc.)
- Teledesic (McCaw and Microsoft)
- SATIVoD (Alcatel Espace)

IRIDIUM

The IRIDIUM system is the prototypical Big LEO MSS. Now owned by the Iridium, Inc. world-wide private investor consortium, IRIDIUM was originally proposed by Motorola engineers, and was the first Big LEO concept to be announced (June 1990). The consortium includes Motorola (the system prime contractor), key subcontractors Raytheon (main mission antennas) and Lockheed Martin (flight system bus), Sprint, and at least twelve international investors. Many of the international partners are consortia formed specifically to solicit regional investment interest. IRIDIUM is designed to deliver voice, data, fax, paging, messaging, and locator services to all points on Earth.

To achieve global coverage, the system architecture requires 66 operational satellites and 6 on-orbit spares deployed equally in six polar (86.4 degree) circular orbits at 780 km altitude. The system will use Ka-band for ground station and cross-link communications, and L-band for the handset link. Unlike most other proposals, IRIDIUM uses a combined FDMA/TDMA protocol, and quadrature phase-shift keying (QPSK) modulation. Each satellite includes three Raytheon phased-array main antennas that handle 16 spot beams each, or 48 beams per satellite. Frequency re-use is achieved by spatial multiplexing.

Iridium, Inc. plans to use as many as three launchers from industrial partner companies: the McDonnell Douglas Delta 2 (able to carry five satellites per launch), the Khrunichev Enterprise Proton (seven satellites per launch), and the China Great Wall Industry Corporation Long March IIc (two satellites each). In light of the recent Long March launch failures, Iridium may rely more upon Delta and Proton launches for full system deployment. The first satellites are scheduled to be launched in late 1996, and commercial service begins in 1998.

The system development is expected to cost $3.4 billion, for which $1.9 billion in equity financing is now complete, and a two-stage bank financing arrangement has just been announced. Air time will cost end users about $3 per minute. The high cost is justified by Iridium marketers by a high quality of service offered, including imperceptible delays. The current market philosophy is that this service will complement cellular service in sparsely populated areas where it is too expensive to deploy a cellular infrastructure. Since the cost of installing ordinary telephone service in some third-world countries is as high as $10,000 for one subscriber loop, services like IRIDIUM could be an attractive alternative. The system will interface to existing terrestrial cellular networks, and the handset will be interoperable with the cellular networks. At the same time, the system will have independence from the ground networks, since calls can be switched through the satellite network alone, by means of satellite-to-satellite links [IRID96a, SWEE93, SUGA93, KLAS92, IRID96b, SPNE96].

ICO

Inmarsat is currently the major commercial provider of satellite mobile radio telephone services, primarily for ships at sea. Inmarsat has formed a new affiliate organization, ICO, to develop a new system (also called ICO – formerly Inmarsat-P or Project 21) to compete directly with Iridium, offering a full range of voice, data, fax, and paging services. In 1995, ICO selected Hughes to be the system prime contractor. Hughes will also have a substantial equity position in ICO. The complete system will include 10 operational and two spare satellites in two intermediate circular orbit planes of 10,355 km altitude, and 45 degrees inclination. Handheld terminals will communicate via L-band/S-band (up/down links), and feeder stations will use C-band frequencies of 5 GHz for uplink and 7 GHz for downlink. Each satellite will support up to 4,500 simultaneous voice calls. The venerable Hughes HS 601 satellite bus will be adapted to handle the call volume. First launch is scheduled for 1998; commercial service begins in 2000. ICO plans a call rate of $1-2 per minute, substantially lower than IRIDIUM's $3 rate, and much lower than the current Inmarsat service prices [EMDM93, SCHN95, MSN94, INMA95].

Globalstar

The Loral/Qualcomm Globalstar system will consist of 48 operating satellites and 8 spares distributed in eight orbit planes at 1,410 km and 52 degrees inclination. Globalstar is a CDMA system with 16 beams per satellite for voice, data, fax, paging, and geo-location services. Like IRIDIUM and ICO, the system will be interoperable with existing ground-based cellular networks, and will extend cellular coverage to areas where cellular infrastructure is now lacking. Unlike these competitors, Globalstar is a non-processing (or bent-pipe) repeater system, and so will not have satellite cross-links and will not bypass the ground networks of current suppliers. This approach was key to Globalstar's effort to involve current telecommunications providers as investors and partners. Call rates are quoted "wholesale" at $0.35-0.55 per minute, since Globalstar service will be resold to end users by telecommunications service providers. First launch is scheduled for 1997, with commercial service beginning in mid-1998. Capital investment will be about $2 billion to achieve full deployment, of which $1.4 billion has been secured [SWEE93, SUGA93, KLAS92, GLOB96, AWST96a].

Odyssey

Like Globalstar, the Odyssey system is a bent-pipe repeater that relies on ground support for call processing. Odyssey is a partnership of TRW and Teleglobe, and will offer the full range of services common to the Big LEO systems from 12 satellites (plus three spares) deployed in three medium-altitude orbit planes at about 10,354 km circular and 50 degrees inclination – an orbit choice that TRW claims is the best features compromise of the LEO-to-GEO altitude range. Coverage will be limited to the major land masses. Both uplink and downlink signaling will be accomplished via spread spectrum (CDMA), which TRW expects will give more efficient spectrum use than FDMA or TDMA. The satellite design is based on TRW's Advanced Bus, which is already included in several current NASA flight projects. Each satellite will weigh about 2,200 kg dry. High onboard power generated (over 6 kW at end-of-life) by arrays of advanced GaAs solar cells will reduce the user handset transmit power to a surprisingly low 0.5 Watt.

The Odyssey system cost, initially quoted at $1.3 billion, is now being estimated at $3 billion. Recent press reports suggest that TRW is having difficulty securing major investment partners. First launch is planned for the second half of 1997. Limited commercial service will start in 1998 with 24 satellites, growing to global coverage with the full constellation in 1999. Odyssey proposes end user pricing of less than $1 per minute, possibly as low as $0.65 per minute. ICO and Odyssey are similar enough in design that TRW is claiming patent infringement by Inmarsat's ICO system [SWEE93, SUGA93, KLAS92, ODYS96, BAIR96, AWST96b, MSN96].

Ellipso

The Ellipso system is being developed by Mobile Communications Holdings, Inc. (MCHI), with development partners including Spectrum-Astro, Inc. for the flight systems, Harris Corp. for communications payloads, and Westinghouse for the ground network. Designed as an extension of the cellular networks for isolated and rural areas, Ellipso will also provide position location service to mobile users. Ellipso will consist of two sub-constellations: Borealis and Concordia. The Borealis constellation comprises ten satellites in two elliptical orbit planes of roughly 7,800-by-520 km, covering the northern hemisphere. The Concordia configuration includes 7 satellites in circular equatorial orbit at 8,000 km, serving the southern hemisphere. This system is therefore a medium-earth orbit system. The spacecraft counts include one active spare in each orbit plane. The constellations are designed to have two satellites visible above the horizon in most places at most times, so that both satellites will be able to receive the uplink signal.

Each Ellipso satellite will handle up to 61 spot beams in a bent-pipe mode, with call processing managed by a ground control station. A CDMA protocol, similar to terrestrial digital cellular CDMA, will be used. Ellipso switching offices will interface with the public switched network. The handsets will be sold initially at $500-600, with prices decreasing as business volume builds. Commercial operation is scheduled to begin in 1998, at a call rate of as low as $0.47 per minute to end users of mobile equipment. Note, however, that MCHI will use value-added resellers to reach the market, so pricing may vary according to market conditions. MCHI must also convince regulators at the Federal Communications Commission (FCC) to reconsider their 1995 decision denying a license for Ellipso on grounds of inadequate financial support [NAUG96, MCHI96, SPNE96a].

Constellation

The original Constellation (formerly Aries) concept from Constellation Communications, Inc. (CCI) was similar to Globalstar: global mobile voice, data, and fax services from 48 satellites in four polar orbit planes at 1,020 km altitude. But CCI has now joined a venture that includes E-Systems, Bell Atlantic, Instituto Nacional de Pesouisas Espacias (INPE) – the Brazilian Space Agency – and Brazil's PTT – TELEBRAS – to serve rural areas of developing countries. The system architecture now calls for 12 ECCO satellites (11 operational plus 1 spare) in equatorial orbit at 2,000 km. The service area is the region between 23 degrees north and south latitudes, which includes 40 percent of the world's population. The technical team now includes E-Systems, Lockheed Martin, and Texas Instruments. At least 1,000 voice-grade circuits per satellite will be provided using CDMA. Spacecraft are planned to weigh 425 kg or less. Other details on ECCO, as well as future plans for extending system coverage, are presently limited. Like many of the other competitors of IRIDIUM, the company hopes to sell air time at a substantially lower price than IRIDIUM. Hand-held and portable units are planned to retail for under $1500 to start. Total development budget for ECCO is estimated to be $500 million. One interesting point about the ECCO system design is that it is largely based on ECO-8 – an original concept design by INPE, and is thus the only constellation concept targeting users in developing nations that was also designed by the space agency of a developing nation [KLAS92, ECO96].

Teledesic

The Teledesic system, proposed as a joint venture between McCaw Cellular and Microsoft, stands apart from the rest of the Big LEO system concepts in many respects. First, it will consist of 840 operational satellites (and as many as 84 spares on orbit) in 21 distinct polar orbit planes for near-global coverage. Each orbit is 700 km circular, at 98.2 degrees inclination. All uplink and downlink transmissions, including direct to hand-held units, will occur in the Ka-band, with 64 spot beams per satellite, onboard processing, and rapid hand-off required. The 700 kg spacecraft will be 3-axis stabilized, with articulated solar panels, and a large deployed phased-array antenna. Initial operation is planned for 2001, with funding of $9 billion through full deployment, or nearly three times the cost of IRIDIUM, which is the next most expensive MSS.

The Teledesic system is envisaged to provide full voice, data, and video services, including data rates of up to 2 Mbps – far higher than any rate claimed by the systems described in the preceding paragraphs. This is clearly far more ambitious than the voice telephony services proposed by most competing Big LEO systems: one reviewer characterizes Teledesic as "Internet in the Sky." Other vendors have floated proposals for similar services, but using geosynchronous platforms (discussed below). These concepts share the goal of offering very high bandwidth to all users and applications at very low rates [SUGA93, KELL94, MSL96, LEVI96].

SATIVoD

The most recent entry in MSS concepts is SATIVoD. Proposed by Alcatel Espace of France, SATIVoD consists of 60 satellites to provide interactive video-on-demand and multimedia services, especially to areas where population density won't support the expense of cable installation. The satellites would be placed in circular orbit at 1,600 km altitude. The user terminal is a television and converter box. Other details are not available for SATIVoD [DESE96, ALCA96].

2.1.3 GEO Mobile Telephony Services

Qualcomm, Inc.

Qualcomm currently provides messaging service and RDSS for the continental US using leased geostationary satellite links in the Ku band. The service is provided mainly to long-haul trucking companies, and currently has over 140,000 subscribers. Service enhancements will include lower cost terminal equipment to include monitoring stationary trailer location and status, enabling a trucker to charge customers for their use of revenue equipment as storage space [QUAL96]. Qualcomm does not operate its own satellites; the company is mentioned here because of its established market position providing services similar to those proposed for Little LEO systems.

American Mobile Satellite Corporation (AMSC)

American Mobile Satellite Corporation is jointly owned by Hughes Communications, Inc., AT&T/McCaw Cellular, Mtel Corp., Singapore Telecom, and General Dynamics. This company is providing a telephony MSS via three geosynchronous satellites. The satellites will be built by Hughes Aircraft, and General Dynamics provides the launch service. AMSC-1, an HS-601 bus, was launched in 1995, and is now anchoring the SKYCELL service for North America, with additional coverage for Central America. AMSC-1 weighs approximately 1,600 kg, and uses six spot beams to provide full digital (FDMA) coverage. The service is aimed at potential land mobile users outside the coverage areas of cellular, and at long-haul fleet communications. The dual-mode cellular/satellite handsets, manufactured by Mitsubishi and Westinghouse, are priced around $1800, with a basic monthly charge of $25, and $1.49 per minute of air time. Geo-location will be determined by means of GPS [AMSC96].

Inmarsat

Inmarsat is the other major operator of mobile/portable telephony satellites, which are in geosynchronous orbit. Inmarsat operates four of its own satellites, one in each of four coverage regions, and leases operating capacity on the Marecs B2 for the eastern Atlantic Ocean area. Lease agreements also cover six spare GEO satellites (at least one in each region) in the Intelsat and

Marisat series. They currently have several user services, designated Inmarsat A, B, C, and M, and plan a new offering for global paging, called Inmarsat D. The Inmarsat A, B, and M services all require heavy, stabilized directional antennas at the mobile unit. The cost to the user of these Inmarsat services is currently relatively high. The portable earth stations cost $15,000-40,000, depending on the service selected.

Inmarsat C

Inmarsat C is a newer-generation system that supports briefcase-sized ground terminals for two way store-and-forward communications. To operate on a mobile platform, the system can use either a high-gain or an omnidirectional antenna. Companies such as Comsat, Mobile Telesystems, and Glocom offer portable earth-stations that can be operated in the field, but from a fixed position. These units typically fit in a briefcase and weigh 15-20 lb. They employ flat microstrip array antennas that fit in the top of the briefcase. Comsat expects to offer a new generation portable earth station in 1996. It will be about the size of a laptop and will weigh 6 to 8 pounds. Inmarsat C is the least expensive at $4,000-10,000, with air time costs about $5 per minute [EMDM93, INMA95, BURG94].

CelSat America, Inc.

CelSat America, Inc., an affiliate of Titan Corporation, plans three satellites that will provide full coverage of the US by creating a cellular system consisting of 100 "super-cells" formed by multi-beam antennas on the satellites. CelSat claims that its handsets will only need a transmit power of one-tenth of a watt. That such a low level of power is required would seem to contradict one of the chief justifications for LEO systems: that a short path length is required to achieve low transmit power levels. In high-traffic urban areas, the system will be augmented by a ground-based cellular system. CelSat's call management system will automatically choose the best routing between satellite and all-cellular. The satellite network will support 50,000 mobile subscribers. The network will be capable of providing voice, fax, data services, and RDSS. CelSat claims that airtime for voice service will cost $0.20 per minute by 1999, which is much lower than for any other system. In addition, the system will have a wideband capability for mobile video transmissions. A CDMA protocol will be employed for transmission in the 2 GHz band [SUGA93, COLE95, NTIA96].

Other GEO Services

Several other ventures have filed requests with the FCC to use the Ka-band for satellites in geosynchronous orbit. Most of these appear to compete directly with the Teledesic concept, in offering broadband multimedia communications – "bandwidth-on-demand" as one claims. What is not yet clear is the degree to which these services would address the needs of mobile users. Also, some of these plans may have been submitted to the FCC as place-holders to ensure that the sponsoring companies have some chance at slot allocations. While the ACTS program established the feasibility of many of these space-based services, only AstroLink has explicitly acknowledged its ACTS heritage. Table 2-2 summarizes features of eight proposed systems [ASKE95, ATT96].

Table 2.2
Prospective Ka-Band Systems for Broadband Multimedia Services

Concept Name	Applicants	Number of Spacecraft	Comments
VoiceSpan	AT&T	12	"Advanced multimedia infra- structure of the future"
Galaxy, or Spaceway	Hughes	15	Would use Ka and Ku-bands $3 billion estimated cost
AstroLink	Lockheed Martin	9	Service for business and common carriers $4 billion estimated cost ACTS heritage claimed
CyberStar	Loral Aerospace	3	"High-speed" service for business and residential users $1 billion estimated cost
GE Americom	General Electric subsidiary	9	No details known
Millennium	Motorola	4	$2.3 billion estimated cost
Echostar	Echostar Communications	2	Data, video, and video conferencing
NetSat 28	NetSat	1	Fixed, broadband services

2.2 FUTURE APPLICATIONS

Discussion of the proposed service offerings in the previous section indicates several applications that may be supported by MSS systems within the next 5-10 years. This section highlights several of these applications, and discusses their potential value to mobile users.

2.2.1 Mobile Packet Data

Present-day applications of LEO small-satellite architectures are limited mainly to low bandwidth packet data store-and-forward services using single satellites. While such services are currently limited to a relatively small number of users, the potential market could be much larger when applications such as global paging are considered, and when the number of satellites increases. Satellite-based paging could be competitive in regions of the world that do not yet have a ground-based paging broadcast system, or other telephony infrastructure.

The packet services to be provided by the Little LEOs and Inmarsat D have many potential applications. These include global paging and electronic mail, security alarm relay, maritime communications, remote control of untended facilities, telemetry relay, disaster relief and emergency communications, and supplemental military communications.

2.2.2 RDSS

Another emerging application is the RDSS, or the combined packet messaging and geo-location service. By measuring the Doppler wave form of the radio signal emitted from a LEO satellite passing overhead, it is possible for a ground-based observer to calculate the distance from the satellite ground-track and, using an ephemeris, also determine the along-track coordinate. The accuracy of such a determination is on the order of 500 to 1000 meters, although improvements may be possible. (See the previous discussion of Orbcomm's geo-location service.) The service can be competitive with GPS for those applications where the reduced accuracy is acceptable in exchange for lower hardware cost. For example, when the position data must be relayed by radio, the same RDSS transceiver can be used for both geo-location and radio relay, whereas a separate radio must be used for radio relay if position is determined by GPS.

Some RDSS systems use multiple geosynchronous communications satellites and a time-of-arrival (TOA) distance measurement technique to provide the geo-location information. Unlike a LEO system, these can provide continuous coverage for ground site users. Applications for RDSS include vehicle location for fleet management, delivery routing, service vehicle dispatch, public safety vehicle dispatch, theft recovery, and marine applications such as navigation and emergency location-finding [KRAK94].

2.2.3 Wide-Area Mobile Telephony

Cost-competitive mobile wireless telephony via satellite relay is several years into the future. It is envisaged by its proponents as mainly a supplemental service for regions not now covered by cellular service. In some cases, it is planned as an alternative telephone system for third world countries with inadequate telephone service, and limited resources for installing communications infrastructure. Mobile satellite telephony also encompasses all of the packet data applications, since it will be possible to send data over the network. For data applications, it will allow larger data volumes to be transported, although at higher cost per bit than the Little LEOs. It is possible that some of the proposed architectures would allow other LEO remote-sensing satellites to communicate over the network for space-to-ground relay. This application could serve as a complement to NASA's Tracking and Data Relay Satellite System (TDRSS), or it could be a competitor.

The mobile telephony satellite systems will be able to cover the RDSS type of service. Most of the architectures use CDMA, which inherently allows TOA position measurement. IRIDIUM, which will use TDMA, will incorporate GPS receivers into the handset to determine position. The reasons for doing this are not just to provide a service to the subscriber, but also to support the billing process.

2.2.4 Wideband Data

Of those companies surveyed, only CelSat and Teledesic plan to provide the wideband capability for mobile video. Some of the proposed systems noted in Table 2.2 would also have the capability to support this application. Mobile video transmission does not yet have mass market applications, except perhaps in public safety, where police and rescue vehicles are beginning to carry video cameras on a trial basis for various applications. It can be expected that as the cost of charge coupled device (CCD) video cameras and still cameras decreases, new applications will be found. It may be surmised that wireless networks of the future will evolve a capability to handle video. This will be accomplished by improvements in two directions, improved compression technology and increased available radio frequency bandwidth.

A recent small satellite built by the University of Surrey, called Kitsat-1, carries a low-cost, lightweight CCD camera for earth imaging. This camera has low resolution compared to earth resources sensing satellites, but is indicative of a new direction for commercial smallsats. Since imaging instruments require a high data rate, it can be expected that the communications space-to-ground data rates will increase over today's typical rates [UNWI93].

2.3 EMERGING TECHNOLOGIES

An enabling technology for the LEO satellite networks is the monolithic microwave integrated circuit (MMIC). This technology permits RF circuits to be integrated and miniaturized on a common substrate, just as digital circuits are. The impact of this technology has been mainly on subscriber equipment, such as hand-held cellular telephones, but as a byproduct, satellite circuitry can also be miniaturized, reducing physical dimensions for equipment bays. By increasing the level of integration, not only can the size be reduced, but manufacturing costs are reduced, and reliability is increased. This allows complex RF devices to become mass market products, and thus enables new applications such as MSS. NASA Lewis Research Center is investigating the fabrication of silicon MMICs for such uses as oscillators and amplifiers. The work is being carried out in conjunction with Hughes Aircraft Company and possible collaboration with the University of Michigan [PONC96].

An important and burgeoning application of space technology is vehicle and personal navigation through the use of space systems such as GPS. The new RDSS technology will provide competition to GPS, particularly for those applications in which the location information must be relayed by radio to a remote command and control center. There is little doubt that RDSS accuracies will continue to improve. For example, GPS receivers carried on board the LEO satellites would allow extremely accurate (to 1 m) orbital determinations to be made, which would in turn improve the accuracy of the Doppler geo-location method. GPS can also simplify the design of space-to-ground links that require tracking antennas. The GPS-determined satellite position can be relayed to the ground terminal to guide the pointing of the antenna.

Another area of research in recent years is "microsats," or satellites weighing less than one kilogram. Much of this research was associated with the "Brilliant Pebbles" concept that originated in the organization now known as the Ballistic Missile Defense Organization (BMDO). This research was aimed at reducing the cost of a space-based missile defense system by orders of magnitude. An example of a microsat concept, described in a paper by R. M. Jones of the Jet Propulsion Laboratory (JPL), is essentially a scientific instrument package in the form of an artillery projectile. In another article, Jones describes ultra-miniature components and spacecraft designs including a complete propulsion system weighing less than 3 kilograms, a 250-gram star tracker, and a 100-gram computer [JONE89a, JONE89b].

JPL is now leading NASA's New Millennium initiative to revolutionize the spacecraft development process supporting the space and Earth science programs. Integrated product development teams have been formed to address five areas:

1. Spacecraft autonomy
2. Microelectronic systems
3. Communications Systems
4. Instruments and Micro-Electromechanical systems
5. Modular architectures and multifunctional systems

New Millennium technology validation flights are planned commencing in 1998 with the Deep Space-1 mission, which will demonstrate 17 advanced technologies in areas such as solar power conversion, power management and distribution, electric propulsion, low power electronics, high-density packaging of electronics, Ka-band transponder and solid state power amplifier, and a low mass antenna. Any or all of these could find immediate far-reaching application to LEO/GEO communications satellites. It is also of interest that one of the novel scientific exploration approaches that New Millennium will support is to send a constellation of very small spacecraft to other planets to study global dynamic processes. The potential for synergy between the New Millennium technology program and the MSS consortia is very strong, and is likely to increase as they begin launches.

A development related to commercial LEO satellite networks is the use of unmanned atmospheric platforms that could be used singly or in a constellation as communications relays. Both airplanes and lighter-than-air zeppelins have been suggested as Unmanned Aerial Vehicles

(UAVs) for this purpose. Instead of placing a radio repeater on orbit, a repeater on a single UAV provides local area coverage, and a network of UAVs would extend coverage over a broad area. One obvious advantage of using an atmospheric relay is the relative propagation delay advantage compared to an orbiting repeater. Another is that UAVs can be retrieved for repair and refurbishment, or even for redeployment in another market.

Although UAVs of various types have been proven for many military applications, their use for commercial communications may be problematic. Most importantly, an aircraft is an inherently unstable platform, so system reliability and integrity is an immediate issue. Also, a UAV-based system will require many more units deployed to achieve breadth of coverage similar to satellite-based systems. This raises concerns of operational complexity and safety. Despite these problems, it can be expected that commercial enterprises will soon attempt to demonstrate UAV-based repeaters. A UAV repeater station might also play a role in a satellite-based infrastructure, extending the coverage time of a ground station for satellites below GEO altitude [NAIK, BRCA96].

3. RESULTS

3.1 IMPACT OF MSS TECHNOLOGY ON NASA

A revolution is going on in space technology comparable to the personal computer revolution of the 1980s. This process involves a similar transformation of large-scale systems into small, portable, personal, low-cost systems through miniaturization, higher-scale integration, parts-count reduction, quality improvement, and mass production. Another parallel to the current trend is the telecommunications bypass movement of the 1980s that was precipitated by the breakup of AT&T. It had the effect of breaking up monopolies, increasing competition, lowering costs, and avoiding government regulation and control. Space offers another avenue for bypassing the established communications infrastructures and organizations, especially the government monopolies that control communications in many third world and former eastern-bloc countries.

In the life cycle of any technology, there will be an initial phase that requires a large research and development effort. This will be followed by a progression to commercialization, mass production, and lower costs, until finally, the technology is no longer considered advanced. One of the original purposes of NASA was to pioneer the technologies required for space exploration. The present maturation of space technologies will undoubtedly result in a shift of NASA priorities to other areas of technology development.

In the 1990s, commercial interests will establish new space-based communications infrastructures that will compete with ground-based networks. Expanding on this trend points to a time when commercial companies will provide space-based services directly to end users. At a certain price point, it will become feasible for small private concerns to write proposals, win funding, buy off-the-shelf equipment from a vendor, and put their own satellite in space for research or commercial purposes. (Final Analysis Inc. already plans to offer secondary payload service to this class of user for each of its launches of FAISAT Little LEO spacecraft.) Many aerospace companies already offer standard satellite bus products, and the catalogue of microelectronics subsystems is growing. These commercial developments may permit NASA to refocus a portion of its technology development effort towards other cutting edge areas. One example with potential relevance to the satellite constellation concepts discussed in this chapter is the development of ultra-small "intelligent machines" for spacecraft bus and subsystem design.

The emerging MSS projects will undoubtedly provide many opportunities for cross-fertilization between NASA and commercial applications. NASA-developed technology will feed commercial space developments, and commercial methods of financing and deploying space systems will, in turn, provide models for NASA's efforts to deploy smaller, cheaper systems.

The new space activities stimulate questions: to what extent will future commercial space communications systems be able to support NASA communications requirements, and to what extent can NASA resources, such as a future TDRSS, support commercial markets as well as the primary NASA mission? Posed another way, are the NASA mission and commercial ventures candidates for a dual-use system? Perhaps such questions are not appropriate, but at a minimum, it seems that there should be some impact of the new architectures on NASA design approaches for the future.

NASA programs may benefit from drastic cost reductions in components, space hardware, and launch services as economies of scale and competitive pressures appear in serving a growing community of MSS customers. If the large scale LEO deployments go forward, it may be possible to purchase mass-produced satellite platforms at low cost, and modify these to suit NASA's mission-unique needs. Mass production is the key to lowering the cost of access to space, and will enable many new missions that otherwise would not have occurred. It is possible that by the year 2000 NASA will be able to buy mass-produced satellites, such as the IRIDIUM satellites, modified to perform TDRSS-like functions.

The main technology driver in these developments is miniaturization at the level of mechanical systems, digital electronics, and RF electronics. NASA can take the lead in developing space applications for the miniaturized electronic components developed for consumer markets. Mechanical and propulsion systems, for which there are few commercial counterparts, will continue to be a field uniquely suited to NASA-led development, and for which there is likely to be a growing market of commercial satellite vendors and operators.

3.2 TECHNOLOGY ROADMAP

The following is a hypothetical timeline for the emergence and development of MSS services and related technologies.

1996-1997: Launch of first LEO MSS continues. Worldwide packet store-and-forward service will be available on a limited basis (Orbcomm), or in system test and demonstration (FAISAT). NASA may provide limited ground support to some of these ventures. Expanded service offerings at lower price points from established vendors using GEO platforms.

1997-2002: First launch and checkout of satellites for one or more Big LEO systems, such as IRIDIUM. Initial global MSS service begins after 2000. Further definition of proposed Ka-band multimedia and broadband services continues. In this period NASA should plan for making use of mass-produced MSS technology for similar NASA missions such as space-to-ground telemetry. Off-the-shelf satellite bus products will proliferate, and will be available for use by NASA.

2002-2005: Full scale roll-out of global MSS services. Shake-out of weaker competing companies in LEO services is expected. NASA may be able to buy off-the-shelf satellites for space-to-ground telemetry.

2005-2010: Second generation of MSS designed and partially deployed. Possible on-orbit feasibility demonstrations for broadband systems like Teledesic.

2010-2020: Broadband system(s) deployed and operational. Initial attempts at interoperability among services provided by various constellations to offer a complete array of services to all users.

3.3 FEASIBILITY AND RISK

The technologies used in the Little LEO systems are mature, and will not pose much risk for the companies involved. Conservative design practices will prevail, with advanced technologies being implemented selectively.

The Big LEO systems are technically more complex, but most key components have been demonstrated in other systems. System control issues (e.g., hand-off procedures) developed for ground-based cellular will have to be adapted to the moving cell environment. The number of spacecraft and the attendant launch and development costs may encourage more risk-taking by incorporating new technologies to reduce costs or to offer performance enhancements.

Most of the feasibility and risk issues for the Big LEOs have to do with licensing, capitalization, and market demand. Many of the licenses have yet to be issued, and in some countries, it is doubtful that they will ever be issued. Local political agendas may direct the course of events away from the service goals of MSS providers. The Big LEO developers also require substantial capital investment up front, so they are certain to be competing with each other for the attention of investors world-wide. Recent forecasts of how many Big LEO competitors will survive the first-round shake-out may be based on investment capital limitations as much as on technical issues or slot/spectrum allocations.

The true Big LEO market size and the speed with which each market segment will develop are subjects of much speculation. Fortunes may be made or lost on market targeting and entry strategies. Even if the long-range prospects for market growth are good, there may be more planned capacity in the near term than can be supported by the evolving market. Many of these risk factors are the direct result of having so many competing systems. This increases the risk not only for developers, but also for passive investors, who must be concerned not only with the challenging scope of any Big LEO venture, but also with the question of which one(s) will succeed.

GEO-based services share many of the risks of the Big LEO systems, and add a few that are unique to the orbit altitude. Although the value of geostationary orbits is amply demonstrated by the more than 300 spacecraft on orbit there now, and the system architecture is simpler, GEO systems must be developed and deployed in larger and more expensive increments. System-level modularity won't save much development cost if only a few units are to be deployed. Market research studies have already shown that the built-in delay is unacceptable to many prospective users of voice circuits. Therefore, GEO-based systems may ultimately be at unavoidable cost and performance disadvantages as compared to LEO constellations.

In the longer term, the many technical approaches taken by the group of MSS concepts profiled in this chapter raise the question of whether a seamless global space-based telecommunications infrastructure is foreseeable. For now, there appear to be too many incompatible design choices being made to permit any arbitrary subset of the first generation MSS concepts to be interoperable. Unless a very substantial consolidation takes place before volume launches begin, interoperability seems unlikely for the first generation of satellite constellations.

For the MSS concepts as a group, there are certainly technical challenges, but no apparent technical show-stoppers. There are, however, many pitfalls associated with obtaining favorable spectrum and slot allocations, with persuading bureaucratic and politically motivated government agencies to issue permits and to otherwise become participants in these ventures, and with finding investment partners

One risk factor is worth special note: will there be frequent, timely, low-cost access to space to support constellation deployment? All the MSS concepts presented in this chapter plan to complete first generation deployment within six years at most. Even with "eight-paks" and piggy-backs, deploying three or four complete systems in just a few years is a very ambitious schedule for the world-wide launch industry.

NASA has no direct risk, and may benefit from the impact that these ventures are likely to have on flight system technology and costs. As spacecraft and launch vehicles are built in larger numbers, hardware costs can be expected to decrease, providing a major boon to all space projects, commercial and non-commercial alike.

References

[ALCA96] "Alcatel Telecom Selects Arianespace for the Launch of the 3 Worldspace's[sic] Satellites," press release dated March 18, 1996, as quoted on the World Wide Web at http://www.alcatel.com/news/pressrel/telecom/96_03_19.htm April 26, 1996.

[AMSC96] American Mobile Satellite Corporation corporate literature.

[ASKE95] Asker J., "Corporate Titans Vie for Satcom's Future," *Aviation Week & Space Technology*, October 9, 1995, pp. 24-25.

[ATT96] "AT&T, Others Seek Multi-billion Dollar Satellite Systems," World Wide Web at http://cgi2.nando.net/newsroom/ntn/info/100495/info629_2.html, accessed May 9, 1996.

[AWST95] News Breaks Column, *Aviation Week & Space Technology*, September 18, 1995, p.17.

[AWST96a] *Aviation Week & Space Technology*, January 1, 1996, p. 17.

[AWST96b] *Aviation Week & Space Technology*, March 25, 1996, p. 17.

[BAIR96] Baird, T. and W. Bush, "Odyssey System Overview," TRW Space & Electronics Group, February 1996.

[BRCA96] "E-Mail From Outer Space," article from *Broadcasting & Cable* issue of April 1, 1996, as quoted in the Edupage Newsletter of April 7, 1996, World Wide Web at http://www.ee.surrey.ac.uk/Contrib/Edupage/data/07-04-1996,html#6.

[BREE93] Breed, G. A., "Update on Regulatory Activity," *RF Design*, September 1993, p. 28.

[BURG94] Burgess, J., "Beaming in on a Growth Market," *Washington Post*, February, 1994, p. B1.

[COLE95] Cole, J., "Star Wars. In New Space Race, Companies Are Seeking Dollars from Heaven," *Wall Street Journal*, October 10, 1995.

[DESE96] deSelding, P., "Alcatel Plans Competitor to Teledesic's System," *Space News*, April 1, 1996, P. 1.

[ECO96] "ECO-8 Satellite Constellation," World Wide Web at http://www.inpe.br/eco/ and sub-pages, accessed May 8, 1996.

[EMDM93] EMCI, Inc., "Chapter 6: Mobile and Satellite Data," *The European Mobile Data Marketplace*, 1993, pp. 96-115.

[FAI96] Final Analysis, Inc. company literature.

[FATI96] Personal communication with M. Fatig, Final Analysis, Inc., May 15, 1996.

[GLOB96] Globalstar company literature, January 1996.

[INMA95] Inmarsat Fact Sheets (company literature), Fall 1995.

[IRID96a] Iridium, Inc. corporate literature.

[IRID96b] *IRIDIUM Today*, Volume 2, Number 2, 1996.

[JONE89a] Jones, R. M., "Electromagnetically Launched Microspacecraft for Space Science Missions," *J. Spacecraft*, Sept.-Oct., 1989, pp. 338-342.

[JONE89b] Jones, R. M., "Think Small – In Large Numbers," *Aerospace America*, October 1989, pp. 14-17.

[KELL94] Keller, J. J., "McCaw, Gates Plan to Build Data Network," *Wall Street Journal*, March 21, 1994, pp. A3, A5.

[KLAS92] Klass, P. J., "Low-Earth Orbit Communications Satellites Compete for Investors and U.S. Approval," *Aviation Week & Space Technology*, May 18, 1992, pp. 60-61.

[KRAK94] Krakiwsky, E. J., "Innovations in Vehicle Tracking and Navigation," *GPS World*, February, 1994, pp. 42-45.

[LENO93] Lenorovitz, J. M., "Steady Growth Seen for Commercial Space," *Aviation Week & Space Technology*, March 15, 1993, pp. 83-87.

[LEVI96] Levin, C., "Space Race," *PC Magazine* of March 12, 1996 as quoted on the World Wide Web at http://www.pcmag.com/issues/1505/pcm00011.htm, accessed May 8, 1996.

[LOGS95] Logsdon, T., Mobile Communications Satellites, McGraw-Hill, New York, NY, 1995.

[MCHI96] "The Ellipso Mobile Satellite System," Mobile Communications Holdings, Inc.

[MSL96] "MSL: Teledesic Quick Look," located on the World Wide Web at http://leonardo.jpl.nasa.gov/msl/QuickLooks/teledesicQL.html, accessed May 8, 1996.

[MSN94] *Mobile Satellite News*, May 19, 1994, pp. 1-2.

[MSN96] *Mobile Satellite News*, April 18, 1996, p. 3.

[NAIK] Naik, G., "A Far-Fetched Dream: Messages Via Unmanned Plane," *Wall Street Journal*, p. B1., date unknown.

[NAUG96] Personal communication with J. Naughton, Mobile Communications Holdings, Inc., May 8, 1996.

[NTIA96] "PCS - Emerging Technologies," World Wide Web at http://gopher.ntia.doc.gov accessed April 26, 1996.

[ODYS96] Odyssey company literature, March 1996.

[ORBC96] Orbcomm marketing literature and corporate briefing.

[PONC96] Ponchak, G. E., "Silicon MMICs for Microwave Applications," NASA Lewis Research Center, internal presentation, March 1996.

[QUAL96] Qualcomm corporate literature.

[RENS96] Personal communication with A. Renshaw, Starsys Global Positioning, Inc., May 6, 1996.

[RFDE92] "Global Allocations for LEOs and PCS Created at WARC-92," *RF Design*, April 1992.

[SBN95] *Space Business News*, June 1, 1995.

[SCHN95] Schneiderman, R., "Mobile Communications Satellites Boost Hardware Market," *Microwaves & RF*, February 1995, p. 32.

[SPNE96a] This Week column, *Space News*, April 29, 1996, p. 2.

[SPNE96b] Marketplace Column, *Space News*, May 6, 1996.

[SUGA93] Sugawara, S., "Battle in the Skies," *Washington Post*, September 18, 1993, business section.

[SWEE93] Sweeney, D., "Bird Watching," *Cellular Business*, July 1993.

[UNWI93] Unwin, M., and Y. Hashida, "Found in Space: Tracking Microsatellites with GPS," *GPS World*, June 1993, pp. 32-38.

[VELO95] Velocci, A. L., "OSC's New Venture Awaits Improved Launch Reliability," *Aviation Week & Space Technology*, October 2, 1995, pp. 42-44.

[VITA96a] "VITA Communications Service," located on the World Wide Web at http://vita.org/comm/comm.html, accessed April 25, 1996.

[VITA96b] "VITA Services Description," located on the World Wide Web at gopher://gopher.vita.org:70/00/intl/vita/gateway.c08, accessed May 1, 1996.

Corporate Contact Information

American Mobile Satellite Corp.
10802 Parkridge Boulevard
Reston, VA 22091

Final Analysis, Inc.
7500 Greenway Center, Suite 1240
Greenbelt, MD 20770

Globalstar L.P.
1725 Jefferson Davis Highway, Suite 900
Arlington, VA 22202

Inmarsat
London, England

Iridium, Inc.
1401 H Street N.W., 8th floor
Washington, DC 20005

Mobile Communications Holdings, Inc.
1120 19th Street N.W., Suite 460
Washington, D.C. 20036

Odyssey - TRW Space & Electronics Group
One Space Park
Redondo Beach, CA 90278

Orbital Communications Corp. (Orbcomm)
21700 Atlantic Boulevard
Dulles, VA 20166

Qualcomm
6455 Lusk Boulevard
San Diego, CA 92121

ANNEX 1. ACRONYMS AND ABBREVIATIONS

AAL	ATM adaptation layer
ACK	Acknowledgment
ACTS	Advanced Communications Technology Satellite
ADSL	Asymmetric digital subscriber line
AMSC	American Mobile Satellite Corporation
ANSI	American National Standards Institute
Aries	ATM Research and Industrial Enterprise Study
ARPA	Advanced Research Projects Agency
ATDnet	Advanced Technology Demonstration Network
ATM	Asynchronous transfer mode
BISDN	Broadband ISDN
BMDO	Ballistic Missile Defense Organization
BRI	Basic rate interface
BW	Bandwidth
CCD	Charge coupled device
CCI	Constellation Communications, Inc.
CCITT	Consultative Committee for International Telephony and Telegraphy
CDMA	Code division multiple access
CIR	Committed information rate
CPE	Customer premises equipment
CPU	Central processing unit
DAAC	Distributed Active Archive Center
DLCI	Data link connection identifier
DQDB	Distributed queue dual bus
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
FAI	Final Analysis, Inc.
FAISAT	FAI satellite system
FCC	Federal Communications Commission
FCS	Frame check sequence
FDDI	Fiber distributed data interface
FDDI-I	Fiber distributed data interface (original)
FDDI-II	Fiber distributed data interface (enhanced)
FDMA	Frequency division multiple access
FITL	Fiber-in-the-loop
FTTC	Fiber-to-the-curb
GaAs	Gallium arsenide
Gbps	Gigabits (10^9 bits) per second
GEO	Geosynchronous orbit
GPS	Global Positioning System
HDTV	High-definition television
HIPPI	High performance parallel interface
HSCS	High speed circuit switching
IEEE	Institute of Electrical and Electronics Engineers
INPE	Instituto Nacional de Pesouisas Espacias (Brazilian Space Agency)
IP	Internet Protocol
IPng	Internet Protocol - next generation
IPv6	Internet Protocol - version 6 (same as IPng)
IPX	Internet Protocol - extended
ISDN	Integrated Services Digital Network
ITU	International Telecommunications Union

IXC	Interexchange carrier
kbps	Kilobits (10^3 bits) per second
km	Kilometers (10^3 meters)
JPL	Jet Propulsion Laboratory
LAN	Local area network
LAPD	Link access procedure, D channel
LEC	Local exchange carrier
LED	Light-emitting diode
LEO	Low Earth orbit
LLV	Lockheed launch vehicle
MAC	Media access control
MAN	Metropolitan area network
Mbps	Megabits (10^6 bits) per second
MCHI	Mobile Communications Holdings, Inc.
MMIC	Monolithic microwave integrated circuit
MSS	Mobile satellite system
NACLS	North American Collection and Location by Satellite
NAK	Negative acknowledgment
NASA	National Aeronautics and Space Administration
Nascom	NASA Communications
NCSA	National Center for Supercomputer Applications
NREN	National Research and Education Network
NSF	National Science Foundation
OSC	Office of Space Communications
OTDM	Optical time division multiplexing
PARC	Public Access Resource Center
PBX	Private Branch Exchange
PC	Personal computer
PHY	Physical layer
PMD	Physical layer medium dependent interface
PRI	Primary rate interface
PSCN	Program Support Communications Network
PSDN	Public switched digital network
PVC	Permanent virtual circuit
QPSK	Quadrature phase shift keying
RBOC	Regional Bell Operating Company
RDSS	Radio Determination Satellite Service
RISC	Reduced instruction set computer
SDDI	STP distributed data interface
SDH	Synchronous Digital Hierarchy
SILAS	Study of Issues in Linking ATM Networks via Satellite
SMDS	Switched Multimegabit Data Service
SOHO	Small office/home office
SONET	Synchronous Optical Network
SSMA	Spread spectrum multiple access
STP	Shielded twisted pair
SVC	Switched virtual circuit
Tbps	Terabits (10^{12} bits) per second
TCP/IP	Transmission Control Protocol/Internet Protocol
TDMA	Time division multiple access
TDRSS	Tracking and Data Relay Satellite System
THz	Terahertz (10^{12} Hertz)
TOA	Time of arrival

UAV	Unmanned aerial vehicle
VCI	Virtual channel identifier
VITA	Volunteers in Technical Assistance
VPI	Virtual path identifier
WAN	Wide area network
WDM	Wavelength division multiplexing
WDMA	Wavelength division multiple access
WWW	World Wide Web

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1996	Final Contractor Report

4. TITLE AND SUBTITLE

Technology Directions for the 21st Century
Volume III

5. FUNDING NUMBERS

WU-315-90-81
NAS3-26565

6. AUTHOR(S)

Giles F. Crimi, Robert Botta, Thomas Ditanna, Henry Verheggen, Michael Stancati, Harvey Feingold, and Mark Jacobs

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Science Applications International Corporation
1710 Goodridge Drive
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER

E-10452

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA CR-198532

11. SUPPLEMENTARY NOTES

Project Manager, Denise S. Ponchak, Space Electronics Division, NASA Lewis Research Center, organization code 5610, (216) 433-3465.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 32, 17, 33, 60, and 76

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

New technologies will unleash the huge capacity of fiber-optic cable to meet growing demands for bandwidth. Companies will continue to replace private networks with public network bandwidth-on-demand. Although asynchronous transfer mode (ATM) is the transmission technology favored by many, its penetration will be slower than anticipated. Hybrid networks–e.g., a mix of ATM, frame relay, and fast Ethernet–may predominate, both as interim and long-term solutions, based on factors such as availability, interoperability, and cost. Telecommunications equipment and services prices will decrease further due to increased supply and more competition. Explosive Internet growth will continue, requiring additional backbone transmission capacity and enhanced protocols, but it is not clear who will fund the upgrade. Within ten years, space-based constellations of satellites in Low Earth orbit (LEO) will serve mobile users employing small, low-power terminals. "Little LEOs" will provide packet transmission services and geo-position determination. "Big LEOs" will function as global cellular telephone networks, with some planning to offer video and interactive multimedia services. Geosynchronous satellites also are proposed for mobile voice grade links and high-bandwidth services. NASA may benefit from resulting cost reductions in components, space hardware, launch services, and telecommunications services.

14. SUBJECT TERMS

Technology trends; Asynchronous transfer mode (ATM); Switched Multimegabit Data Service (SMDS); Frame relay; Internet; Telecommunications technology; Telecommunications services; Telecommunications costs; Networks; Multimedia; Telecommunications satellites; Low Earth orbit (LEO); Geosynchronous (GEO) orbit; Mobile telephony

15. NUMBER OF PAGES

70

16. PRICE CODE

A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	